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CONTENTS.

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The Application of Electric Heating to Domestic Hot-Water Supply Systems. J. I. BERNARD, B.Sc.Tech. 1

The Evaluation of Transient Temperature Distributions in a Dielectric in an Alternating Field. C. COPPLE, M.Sc., Prof. D. R. HARTREE, Ph.D., F.R.S., A. PORTER, Ph.D., and H. TYSON, M.Sc. 56

Long-Period Ageing Tests on Solid-Type Cables. T. R. SCOTT, B.Sc., and R. C. MILDNER, M.Sc.(Eng.) 67

Electrolytic Condensers........P. R. COURSEY, B.Sc.(Eng.), and S. N. RAY, M.Sc., B.Sc.(Eng.) 107

Discussion on "The Moving-Coil Voltage Regulator".................................. 133

High-Speed Oil Circuit-Breakers: Interpretation of "Single-Loop" Oscillograms. E. E. I. PILCHER, B.A., B.Sc. 143

Discussion on "Plastics and Electrical Insulation".................................. 150

The Limits of Theory in Electrical Machine Design...................G. H. RAWCLIFFE, M.A. 156

Institution Notes.. 159

Advertisements..At end i–xvi

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THE APPLICATION OF ELECTRIC HEATING TO DOMESTIC HOT-WATER SUPPLY SYSTEMS

By J. I. BERNARD, B.Sc.Tech., Associate Member.*

(*Paper first received 2nd June, and in revised form 21st October*, 1938; *read before* THE INSTITUTION *5th January*, 1939, *and before the* WESTERN CENTRE *12th December*, 1938, *also before the* NORTH-WESTERN CENTRE *3rd January*, *before the* NORTHERN IRELAND SUB-CENTRE *17th January*, *before the* NORTH-EASTERN CENTRE *23rd January*, *before the* SOUTH MIDLAND CENTRE *6th February*, *before the* IRISH CENTRE *16th February*, *and before the* NORTH MIDLAND CENTRE *14th March*, 1939.)

SUMMARY

The paper indicates the scope for electric heating of domestic hot-water supplies, and reviews the trend in design of apparatus, including best methods of obtaining quick heating and ample storage. Installation problems and water authorities' requirements are discussed in detail, as affected by practical conditions in houses, flats, and commercial premises. Various systems of charging for energy used for water heating are described, and the cost of supplying energy for different types of heater is analysed.

INTRODUCTION

The heating of water is one of the simplest applications of electricity, but in consequence of the limited amount of heat obtainable for, say, a pennyworth of electricity and the relatively large quantity of heat required for a hot bath, the practical use of electric water heating has been slower in development than other domestic applications.

Early designs of electric water heaters, notably those of C. Orme Bastian and others, were produced before the cost of electrical energy was low enough to permit their economic use; subsequent developments have been the result of a number of solutions of the general problem of providing hot water economically as well as conveniently. Apart from the cost of electricity, largely counterbalanced by high efficiency of utilization, there are many factors in this problem. Among these factors may be mentioned the method of applying heating elements, losses from heaters and pipes, arrangement of existing pipework, composition of water, water authorities' requirements, value of saving in labour, and so forth. It follows, therefore, that electric water-heating apparatus shows considerable variation in design and method of application, but sufficient experience has now been gained to give an indication of the whole field.

TYPE OF WATER, AND USE OF HOT WATER

The kind of water to be heated has an important effect on the design of apparatus. Broadly speaking, water is of two kinds, hard and soft, the former being distinguished by a small content of lime which is deposited in the form of "scale" on heating. Soft water, on the other hand, frequently contains traces of CO_2 or carbonic acid derived from the decaying vegetation of the moorland catchments from which it is usually obtained, and, when heat is applied, it is liable to corrode base metals such as iron and lead. In the soft-water districts, which are mostly north of the Trent, copper has therefore to be used for hot-water storage vessels, these being made in the form of cylinders. Hard water, on the other hand, can be stored in iron tanks, which are more cheaply made in rectangular shape.

Water hardness is measured according to Clark's scale, in which 1 degree is equivalent to 1 grain of calcium carbonate per gallon. Of the total solids stated in this way, only a part is deposited on boiling, this being termed the temporary hardness. Analyses of scale deposits show a variety of salts, principally calcium carbonate, but also calcium sulphate, magnesium hydrate, etc., most of which are not precipitated until a temperature of 180° F. is reached. The composition of different waters varies widely, but ample practical experience has been obtained in all parts of the country so that electric heating apparatus can be designed, as described later, to withstand the worst effects of scale, while soft water presents no difficulties.

As regards the temperature of water from the public mains, there are considerable variations due to weather conditions. In London, for example, the highest and lowest temperatures recorded in recent years are 71° and 38° F. respectively; average seasonal values are: summer, 63° F.; winter, 47° F.; and, for the whole year, 55° F.

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* British Electrical Development Association.

The use of hot water in private households is a factor which is important and yet difficult to deal with in individual cases. In comparison with the amount of hot water used, the quantity of heat required for cooking is a stable quantity. Strange as it may seem, two households equipped with similar hot-water systems and inhabited by the same number of people with similar incomes may use quantities of hot water which vary in the ratio of 3 or 4 to 1; variations of 100 or 200 per cent are common.

Table 1
AMOUNT OF HOT WATER AND ELECTRICITY REQUIRED FOR VARIOUS PURPOSES

Purpose	Water		kWh required
	Gallons	Temperature	
Wash hand basin ..	1¾	105° F.	0·29
Washing up and domestic use	per gall.	150° F.	0·32
Bath (average) ..	25	105° F.	4·16

Hence average figures can only be applied with great discretion in estimating the amount of hot water likely to be used in any particular house. The usual allowance made in designing fuel-fired domestic hot-water systems is 40–50 gallons (at 150° F.) per day for the ordinary small house occupied by 4 or 5 persons, and up to 25–35 gallons per head per day for a block of flats with constant hot water. Experience of electric hot-water systems (in which the energy consumed is almost in direct proportion to the use of hot water) shows that the average use will vary from as little as 5 gallons per day in a working-class dwelling to 150 gallons or more per day in a large house where one or two servants are employed.

The quantity of hot water used for different purposes is given in Table 1 together with the corresponding amount of electrical energy required for heating, assuming an overall efficiency of 88 % and a cold feed temperature of 55° F. (At 88 % efficiency 1 kWh provides 300 gallon-degrees.)

Table 2
POTENTIAL USE OF ELECTRICITY FOR WATER HEATING FOR DOMESTIC PREMISES IN THE UNITED KINGDOM

Approximate number of families	Annual income (£)	Estimated gallons per day (at 150° F.)	Equiv. annual consumption (millions of kWh)
580 000	500 and over	60	4 000
2 900 000	250–500	24	8 000
8 520 000	250 and less	7	6 500
12 000 000			18 500

As a general rule, the use of hot water depends primarily upon personal habit and to a lesser extent upon the ease with which the hot water is obtained and the operating cost of the hot-water installation. Owing to the labour-saving characteristics of electricity, the use of hot water often increases when electric heating is first adopted.

In order to show the possible scope for the use of electric heating in this country, Table 2 is given, based on conservatively estimated figures of daily consumption.

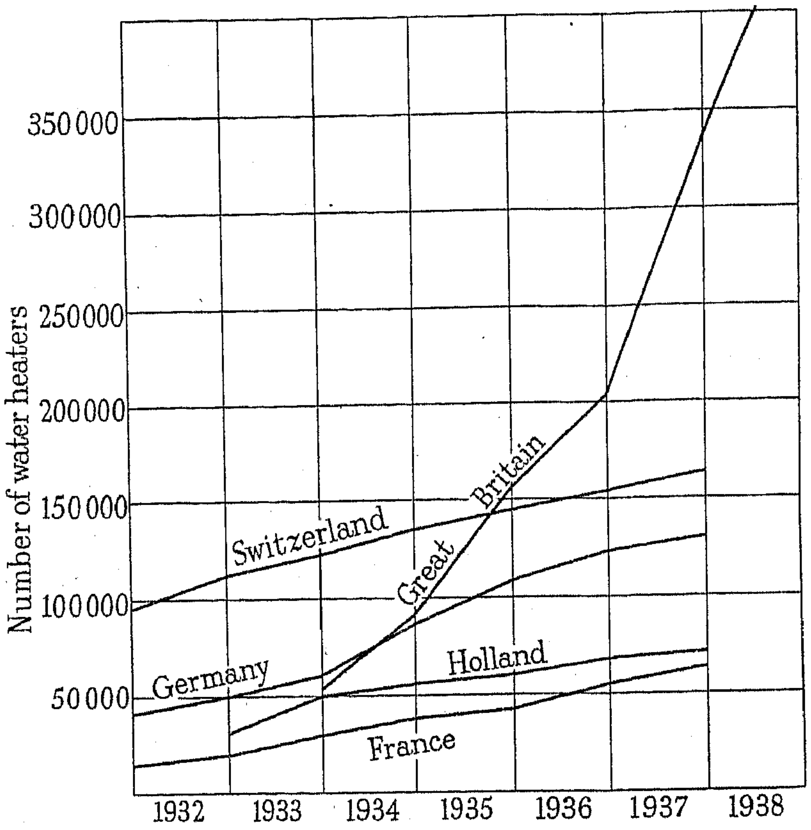

Fig. 1

The total possible consumption of electricity obtained in this way amounts to nearly 3 times the present consumption for all domestic purposes; such a figure may never be realized in practice, but a considerable proportion of it may be regarded as within economic reach, and it therefore affords an indication of the very large scope for electric water heating which exists at present. Fig. 1 shows the estimated number of electric water heaters in

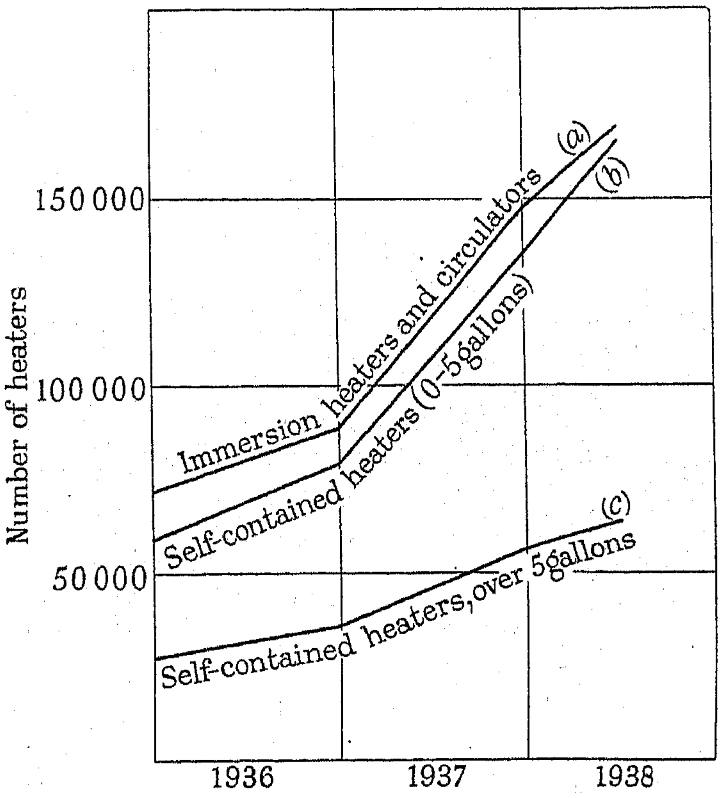

Fig. 2.—Water-heater statistics for the United Kingdom.

various countries and illustrates the progress already made.

There are several towns in the South of England where at least 1 consumer in 4 is now using electricity for water heating, but the proportion for the whole country is much less, being only 1 water heater per 20 consumers, which corresponds to a saturation of 5 %. Compared with this, the percentage saturation in other countries is as follows: Switzerland 17·5 %, Holland 4·5 %, Canada 12·2 %, U.S.A. 4 %.

TYPES OF ELECTRIC WATER HEATERS

Electric water-heating apparatus has been continuously developed along two parallel lines, namely (i) the self-contained type of water heater and (ii) the separate immersion heater for fitting in an existing hot-water storage tank or cylinder. These two main types should be regarded as complementary rather than as competing with one another, because, although there may be many cases in which either can be used with equal satisfaction, there is a large number of cases in which either one type or the other is preferable. As the complete water heater embodies many of the features found in the simpler immersion-heater installation, the former will be described first; it may be noted, too, that the total number of self-contained heaters in use is somewhat greater than the total number of immersion heaters (see Fig. 2).

Both types operate on the storage principle as used in hot-water systems heated by solid fuel, the limited amount of heat obtainable from the amount of electrical power furnished by the size of cable and wiring in the ordinary house, precluding instantaneous heating at a useful rate. For example, a 4-kW geyser cannot raise more than 0·45 gallon of water per minute from 55° to 105° F., and will thus require at least 1 hour to give a hot bath.

SELF-CONTAINED WATER HEATERS

Early electric water heaters owed a good deal to Continental design, but during the last 15 years British-made heaters have been developed to suit the requirements of the public and the conditions of use, particularly hard water, found in this country. Designs have in fact become so stabilized that a British Standard Specification has been drafted and will soon be issued.

General Construction

Electric water heaters consist of a water container surrounded by heat insulating material contained in an outer metal case and fitted with a heating element, thermostat, and pipe connections. The shape is usually that of a vertical cylinder, as this (excluding a sphere, which is hardly practicable) gives the least surface and therefore the minimum radiation loss for a given capacity; in addition, a cylindrical shape is economical to manufacture. The heating element and thermostat are mounted on an " apparatus plate " in the bottom of the water container in the smaller sizes which are made for wall fixing, or horizontally in the side of large heaters which, on account of their weight, have to stand on the floor.

Water Container

This is usually made of sheet copper, jointed by lapping or welding. A sufficiently strong construction can be assured by the container withstanding a pressure test of 50 lb. per sq. in. without permanent deformation. This pressure corresponds to a head of water of 115 ft., which is much greater than the majority of water heaters have to withstand in practice, the working head being at the most no more than the height of the ball-valve tank in the roof of the house. The majority of containers are tinned internally and externally by a hot dipping process, but the necessity for tinning is a debatable point. It was originally adopted to rule out the possibility of contamination—an important matter for small heaters, the water from which is often used for culinary purposes—but recent research seems to show that even when hot water is standing for many hours in an untinned container such as the ordinary domestic hot-water storage cylinder, the amount of copper absorbed is extremely minute, far less than the amount which might be harmful to the human body. It appears, therefore, that tinning is unnecessary, at any rate for heaters larger than 5 gallons, such sizes always being fed from a ball-valve tank, the water from which is not considered by most people to be fresh enough for culinary purposes.

Inlet and Outlet Connections

Water is admitted through a vertical inlet pipe at the bottom of the container, the open end of the pipe having a baffle (generally of mushroom shape) fitted over it to prevent the incoming cold water mixing with the hot contents. With an effective baffle the stratification is so good that 75 % to 85 % of the capacity of the container can be drawn off without the outlet temperature falling more than a few degrees.

The outlet connection is led by means of an internal stand-pipe through the bottom of the container, and in pressure-type heaters (described below) a second outlet pipe is provided at the top of the container for connection to the expansion pipe.

Heating Element

Various methods are used for mounting the resistance wire inside a tinned copper tube suitable for immersion in the water to be heated. There are two main types, the first in which the resistance-wire spirals are mounted in porcelain or steatite insulating formers (in the removable-core pattern these may be withdrawn without disturbing the water joint), and the second in which the resistance wire is solidly enclosed in mica or cement insulation within a flat blade or tubular sheath. Since the temperature of the external surface of the heating element, so long as it is free from scale, is little higher than that of the water, there is no difficulty in designing a complete element so that the operating temperature of the resistance wire is sufficiently low to avoid deterioration and so ensure very long life.

When the water is hard, however, and scale may be deposited on the heating element, some means of preventing the temperature-difference between wire and water rising to an excessive value must be adopted. The deposition of scale depends upon the temperature of the water at the surface of the heating element. This is higher than the maximum temperature of the bulk of the water because circulation is not sufficiently rapid to remove the film of water in contact with the element surface, and local boiling may take place. The amount of scale deposited therefore depends upon the density of heat transmission through the surface of the heating element, and it is found that if this can be reduced to 10 watts per sq. in. of surface, scaling is slight. Another method of preventing deleterious scaling, which is probably preferable, is to make the heating element so long and so thin and of such a shape that its expansion and contraction during heating and cooling is sufficient to fracture and throw off the deposit of scale, and thus prevent it from adhering in any dangerous thickness. The design of such " self-descaling " elements is largely empirical, but none the less successful. Ample space must, of course, be allowed around and below the heating elements for the accumulation of scale, which may with certain kinds of water fall off in large flakes.

Chlorination, which is adopted to purify some water supplies, generally tends to reduce the amount of scale formed.

It may be noted in passing that electric water heaters are unique among all the various alternative methods in that the action of hard water does not impair their efficiency. With all fuel-fired appliances the deposition of scale, which has poor thermal conductivity, increases the temperature gradient between water and combustion chamber, thereby reducing the heat usefully employed.

Table 3

STANDARD SIZES AND LOADINGS

Capacity	Loading
gall.	kW
1½	0·75
3	1·0
5	1·0
12	1·5
15	1·5
20	2·0
30	3·0
40	3·0
60	3·0 or more as required
80	
100	

Loading

The heating elements are wound so as to give a loading in kilowatts which will suit the general design of the water heater, i.e. the space available and quantity of water, without unduly increasing the heat density of the element, the thermostat cycle, and other factors. Normal loadings for various sizes of heater are shown in Table 3. These have been adopted as the result of considerable experience gained both by the manufacturer and by the supply engineer. (As most water heaters are loaned on hire the supply engineer is naturally anxious to ensure that the great potentialities of the domestic water-heating load in respect of improvement of load factor are realized to the fullest possible extent.) Originally the loadings of self-contained water heaters were based, except in the smallest sizes, on a recuperation period of 8 hours to suit the Continental method of supplying energy for water heating at a specially low rate during the night. With this method it is an advantage to the supply authority, and no disadvantage to the user, for the recuperation period to be as long as the charging period desired, e.g. 10 p.m. to 6 a.m.

Early experience in this country indicated, however, that a water heater which gave only a limited amount of hot water per day was not popular, and so the higher loadings shown in Table 3, which correspond to a recuperation period of 4 hours or less, were adopted for use on ordinary 24-hour tariffs, and many years' experience has proved that such loadings are satisfactory in the large majority of cases.

It should be pointed out, however, that the standard loadings shown in Table 3 may be increased if required to meet exceptional conditions. As a general rule it is best to choose a larger heater rather than a higher loading in order to give a greater output of hot water; but, for instance, in a case where a 20-gallon heater would just fit the space available and the normal loading would be insufficient, a 3-kW element might be fitted. Apart from such special cases, standard loadings should not be exceeded. It is, in fact, axiomatic to choose electric water heaters on the basis of their capacity rather than their loading; they are essentially thermal-storage appliances, and no practicable increase in loading can entirely counterbalance shortage of hot water stored.

Thermostat

The design of a suitable thermostat is straightforward; a tube and rod, or alternatively two flat strips of metal, having different thermal coefficients of expansion—for example, brass and invar—are used, the relative movement being made to operate the switch portion, which may be of the familiar mercury-and-glass type or of the short-break magnetic blow-out type* for alternating current. The thermostat differential, i.e. the difference between cutting-in and cutting-out temperatures, is a matter of some importance in the design of a satisfactory water heater. If the differential is too large the minimum output of hot water, when drawn off just before the thermostat is due to close, may be appreciably less than the rated capacity, thus reducing the usefulness of the appliance in service. On the other hand, if the differential is too small, so that the thermostat frequently switches on the current without water being drawn off, the temperature at the top of the heater may build up to an objectionable extent, possibly leading to boiling of the water. The differential depends, other things being equal, upon the length of the thermostat stem; common values are 10 to 15 deg. F. for lengths up to 12 in., and 5 to 10 deg. F. for longer stems.

A further point which affects the design of a complete water heater is the relation of the calibration of the thermostat to the temperature of the water. A thermostat by itself is calibrated by immersing the whole of the stem in a bath of water at a uniform temperature, but the temperature of the water in the heater can differ slightly from the thermostat calibration according to the disposition of the thermostat in the heater, the temperature gradient from top to bottom of the water heater, and other details. So that if the temperature of the water in the top of the container is to be the criterion, the manufacturer may have to supply a calibration chart relating thermostat settings to draw-off temperatures.

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* W. M. THORNTON: "The Micro-Gap Switch," *Journal I.E.E.*, 1937, vol. 80, p. 457.

In soft-water districts, where no scale is formed, thermostats may be safely set to give a draw-off temperature of 190° F. in order that the maximum amount of heat may be stored. In hard-water districts it is advisable to limit the temperature to 180° F., the point at which the most scale begins to form; and where the water is very hard, lower temperatures of 150° to 160° F. are advisable, depending to some extent upon the scale-forming propensities of the particular heater concerned.

Lagging

The heat insulation used for lagging the outside of the water container is particularly important for self-contained heaters which are permanently connected under the control of the thermostat to the electricity supply. Various lagging materials are available, but granulated cork, thoroughly dried, is used almost exclusively on account of its relatively high insulating value, cheapness, adaptability, and permanence. The thickness of granulated cork lagging commonly used varies from 1½ in. to 2 in. in the smallest sizes to 2 in. to 3 in. in the larger sizes. Fig. 3 shows the variation in heat loss with thickness of lagging for a small heater.

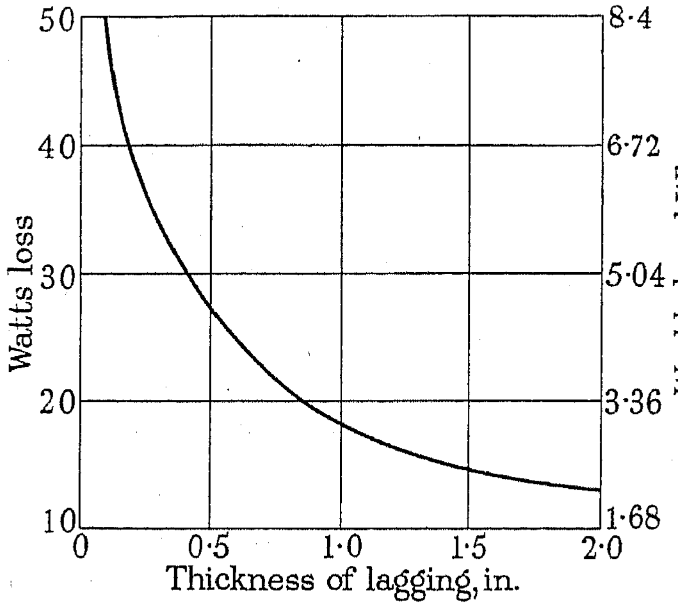


Fig. 3.—Variation of heat loss with thickness of lagging (burnt granulated cork) of 1½-gallon water heater. Temperature 170° F.

Heat Losses

The total heat loss from a self-contained water heater includes, in addition to that of the lagging, the losses due to pipes and other metal connections between the water container and the external case. These additional losses can be reduced considerably by careful design, so that the total heat loss is made very small. The usual method of ascertaining the magnitude of the loss is to measure the energy consumed over a period during which no water is drawn off. Easily-obtained figures per 24 hours are 0·75 kWh for the smallest size and 2 kWh for a 12- or 15-gallon heater. It should be noted, however, that such figures for loss when no water is drawn off do not apply to ordinary working conditions. In use, not only is the average temperature of the contents of the heater below the maximum, but when water is drawn off the apparatus plate is covered with cold water and, as a large proportion of the heat losses from a well-designed heater are from the apparatus plate, the average losses are considerably reduced, and may be only 50 % of the maximum.

Fig. 4 illustrates this argument graphically by showing the relation between the consumption of electricity and the output of hot water per week, as measured by a water meter. The relation varies somewhat, owing to fluctuations in cold-water temperature throughout the year, but if a straight line is drawn through all the readings obtained it is found to cut the zero-output line at 14 kWh, which is much less than the standing loss for a 60-gallon heater with no water drawn off. From this straight line, a working-efficiency curve has been calculated for the relatively light load under which this particular heater was working. The working efficiency of an electric water heater, even with lengths of piping connected to it, is frequently in excess of 85 % with little use and may be 95 % for heavy duty. For example, in one series of practical tests on 60 heaters, mostly of 30-gallon capacity, the following average results were obtained: 44·1 gallons of water per day raised from 62° to 150° F. required 12·15 kWh, i.e. 3·63 gallons per kWh, giving an overall working efficiency of 93·5 %.

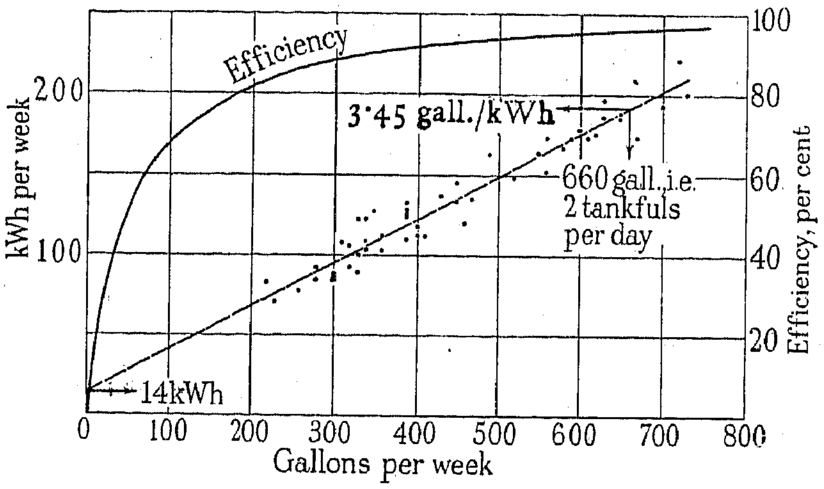


Fig. 4.—Weekly hot-water output and energy consumed by 60-gallon heater working at 150° F.

Points represent readings throughout 1 year. Through these points a straight line has been drawn, and the efficiency curve calculated from this.

Pipe Sizes and Fixing Centres

In consequence of the foresight of the Electric Water Heating Committee of the British Electrical Development Association, standard sizes of inlet and outlet pipes and of fixing centres for wall-mounted heaters were agreed some time ago, and all the leading manufacturers have adopted them. This has resulted in much simplification of installation and service work.

Definition of Types

Self-contained water heaters are made in various types, depending upon the way in which water is delivered to and withdrawn from the container.

Non-pressure type.

The supply of water is controlled by a tap in the inlet pipe, the hot water being displaced by an overflow leading to an open outlet spout.

Pressure type.

The water is supplied from the usual ball-valve gravity feed tank in the roof, and the outlet can be connected to a number of hot taps; with this type of heater it is essential that an expansion pipe should be provided terminating at a point above the ball-valve tank and thus forming a hydrostatically balanced system free from the danger of bursting. A safety valve which is sometimes used abroad as an alternative to an open expansion pipe is not approved in this country, owing to the possibility of it becoming stuck and failing to act.

Cistern type.

This has a self-contained ball-valve tank in the upper part of the casing. As it forms a complete hot-water system it may be connected direct to the cold-water main and piped to supply a number of hot taps. The pressure in a cistern-type heater being limited to the small head of water between the bottom of the container and the top of the ball-valve tank, this type of heater is frequently made in rectangular form to save space. The heater must be fixed above the taps to be supplied, and an overflow pipe fitted to the cistern.

Small Heaters

Small water heaters (up to 5 gallons) are so extensively used, particularly the 1½-gallon size, that they merit special attention. Their popularity is due to the fact that they provide a "constant hot water" service greatly superior to existing facilities at a cost within the means of a large majority of users. Small quantities of really hot water are most frequently required at the kitchen sink, and a small non-pressure type heater can be readily installed in this position, the inlet valve being connected by a short length of pipe to a T-piece inserted behind the cold-water tap. As the latter invariably provides fresh water direct from the main for drinking purposes, the hot water from the heater can also be used for culinary purposes and thus save time in cooking.

The electric water heater is, in fact, the modern counterpart of the large kettle which, in the days of coal ranges, was usually kept on the hob. Its utility is illustrated by Table 4, which gives a typical list of draw-offs during a normal day.

Table 4

Pints	Purpose
3	Breakfast
4	Washing up, with 4 pints of cold water
16	Housework, with 24 pints of cold water
5	Cooking
8	Washing up, with 8 pints of cold water
3	Tea
4	Washing up, with 4 pints of cold water
5	Sundry requirements
—	
48 or 6 gallons (at 180° F.), i.e. 2·5 kWh per day	

The daily output of 6 gallons, or 4 times the capacity of the heater, is considerably greater than the service usually required from larger heaters, the sizes of which are determined by peak loads for hot baths rather than by steady use.

This relatively high duty of the 1½-gallon heater makes the scaling problem more acute with hard water, and the large field available to such a popular appliance has resulted in greater attention being paid to its design and construction, particularly in the following respects.

Anti-drip Device

As water expands approximately 4 % in volume when heated through a temperature-rise of 150 deg. F., dripping will take place from the open outlet of a non-pressure type heater unless some means are employed to prevent it. Such waste of water is not approved by water authorities, and is apt to be a source of annoyance to the user. Various forms of anti-drip device are in use, the most common being a siphonic trap formed at the top end of the outlet pipe so that when the flow of water through the heater ceases as the tap is turned off, the level of water in the container drops slightly to allow for subsequent expansion without dripping from the outlet. This means that when the tap is turned on again, water does not flow from the heater until a few seconds have elapsed, but this slight delay is not a serious drawback. The design of a siphonic anti-drip device which will work satisfactorily under all conditions involves a careful proportioning of the various parts, and even then the action may be impaired by variations in water pressure. For this reason, and also to prevent water being discharged by excessive pressure from the vent at the top of the heater, a restricting washer is often fitted to the inlet tap. In order to avoid having to fit different-size restrictors on site, and also to cater for cases in which the water pressure varies at different times of the day, one make of heater is now fitted with an automatic pressure-reducing valve.

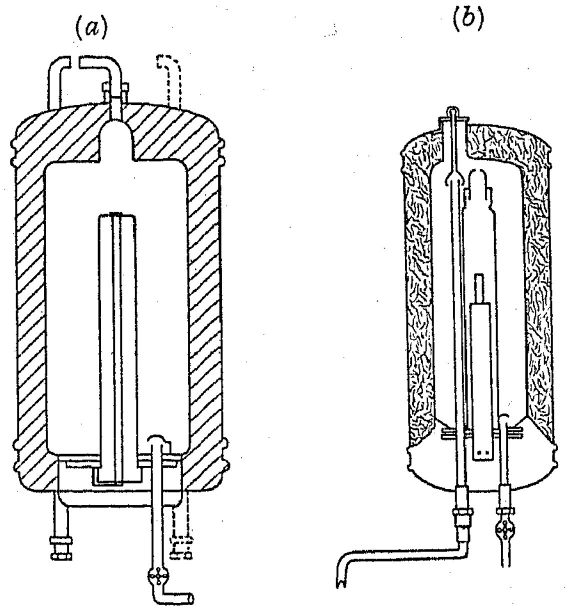


Fig. 5A.—Special anti-scaling designs of 1½-gallon heaters.

(a) Top-outlet (removable) type.
(b) Indirectly-heated type (heating element in automatically-filled large tube to give low rate of heat transmission to water passing through heater).

Other forms of anti-drip device are in use, one of the latest examples being a design in which the top end of the outlet pipe is fitted with a sliding extension operated by the water tap, so that ample allowance for expansion is made and yet the water can flow out freely immediately the tap is turned (see Fig. 5B).

Designs suitable for Hard Water

As already stated, the problem of scaling is more serious in a 1½-gallon heater than in heaters of larger capacity. Figs. 5A and 5B show three patented designs for reducing scaling troubles and maintenance costs. Apart from the deposit of scale on the heating elements, furring-up is particularly liable to take place at the top end of the outlet pipe, and these designs have been produced with a view to preventing this or in order to simplify removal of scale at this point. In general it may be said that, if these and other special designs are employed, the smallest water heaters will operate for at least a year on very hard water before they need to be descaled.

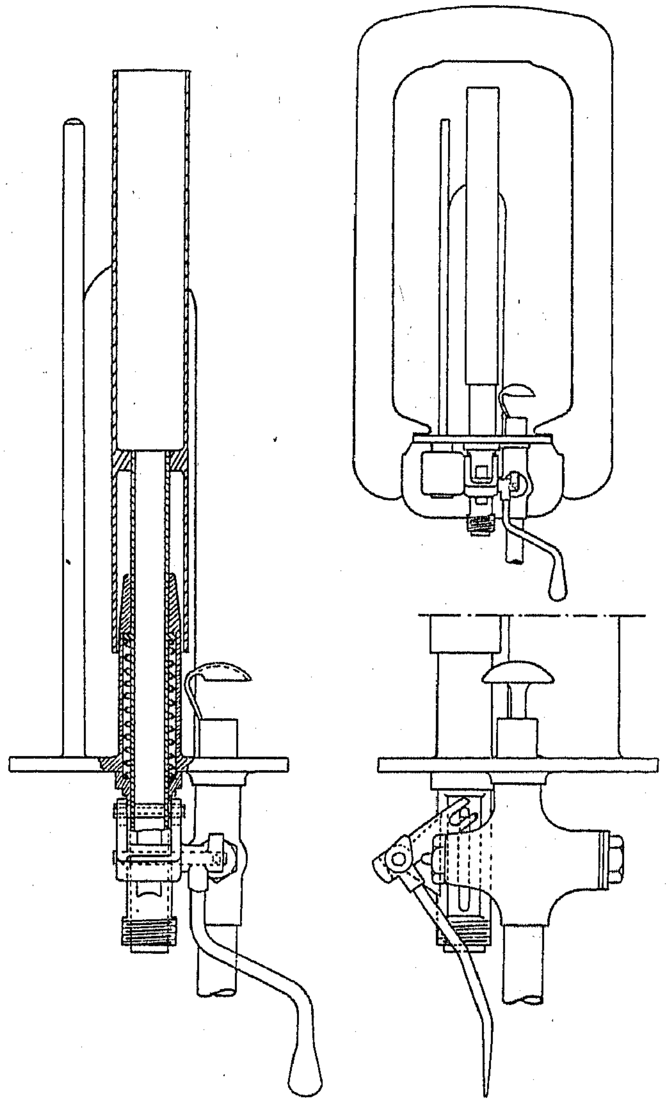


Fig. 5B.—1½-gallon heater, indirectly-heated type.

The element is enclosed in a jacket filled with heat-conducting material to reduce rate of heat transmission. Detail drawings show movable flow tube actuated by handle.

Larger Heaters

The design of larger heaters (12 gallons or more) suitable for supplying all the taps in the house, including the bath, has been developed on similar lines to those adopted in the design of smaller sizes. The principal difficulty is not the interior arrangements, but the problem of adapting such relatively bulky appliances to the exigencies of space in the modern bathroom or kitchen.

The choice of size of heater to be installed in any particular case is governed by the number of hot baths required in succession. As each hot bath requires a minimum of 10 gallons of water at heater temperature, the 20-gallon size is the smallest that can be used in houses requiring two hot baths in quick succession. The capital cost and space required for this and larger sizes of water heater are fairly considerable, with the result that the smaller sizes of 12 and 15 gallons are more commonly used in small houses, the members of the household making themselves accustomed to the type of hot-water service provided by this kind of water heater, a service which will give three or four good hot baths during the day provided there is a minimum interval between them of 2 or 3 hours depending upon the exact sizes of heater and bath, and upon the operating temperature. This interval is not much greater than that required with the conventional fuel-fired hot-water system installed in small houses, and experience shows that many users will readily make any necessary alteration to their habits for the sake of the convenience and consistent performance of this type of electric water heater.

Apart from the normal cylindrical shape, there is a tendency for the larger water heaters to be manufactured in special shapes so that they can be fixed in spaces which are otherwise of little value.

It is, in fact, one of the most important practical advantages of the use of electricity for water heating that tanks can be made to fit in any space available, and it is quite common for hot water supplied in offices and other buildings to be fed from a " made to measure " heater fitted in an odd corner otherwise unused. In domestic premises, special forms of water heater of this kind are most frequently made to fit under a draining board at one side of the kitchen sink, or sometimes in rectangular form to fit in the linen cupboard. Such heaters are generally made in the form of galvanized-iron tanks, surrounded by granulated-cork insulation and enclosed in a sheet-steel case of the requisite dimensions, a standard immersion heater and thermostat and the necessary pipe connections being fitted in the most convenient positions. The adaptability of electric heating applied in this way is becoming known in the building industry, but the efficiency of most water heaters of this kind made up by builders does not compare favourably with that of the factory-made article.

IMMERSION HEATERS AND CIRCULATORS

Immersion heaters, i.e. heating elements designed for fitting in the side of existing hot-water storage tanks, have been used for a great many years on account of the low capital cost of this type of electric water-heating installation, and also because little or no pipework alteration is required. The installation problems are discussed later, as it is thought appropriate to deal first with the design of apparatus.

As in the case of self-contained water heaters, the heating elements are made in various ways, but for immersion heaters the cement-filled element has been extensively used, a high wattage being possible in a relatively small space and the element being self-descaling; one pattern of 2-kW element, for example, consists of two hairpin-shaped loops 9 in. long and $\frac{5}{16}$ in. diameter, the whole mounted on a boss no larger than 1½ in. In other types of element, the resistance wire is wound on insulating formers shaped so as to avoid sagging of the wire and fitted inside a tinned brass or copper tube.

Standard types of thermostats are used in connection with immersion heaters; they are often mounted on the same fixing flange, but more certain action is usually obtained if the thermostat is fitted some distance—6 in. or more—away from the heater, preferably higher, and offset so that the thermostat is out of the way of the hot water flowing upwards from the heater.

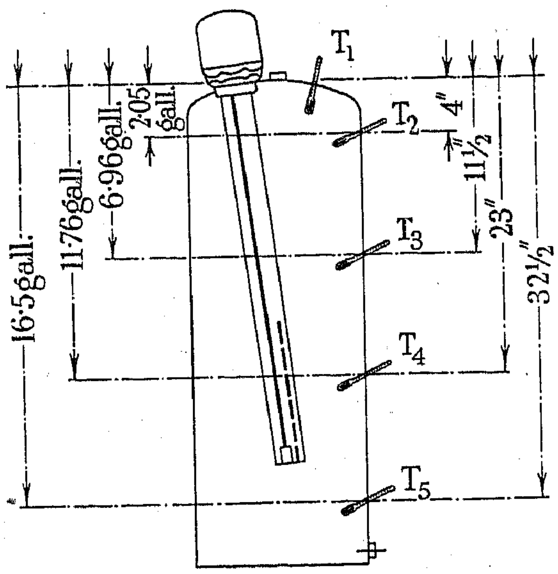


Fig. 6A.—Key showing alternative arrangements of heating elements in thermostatically controlled circulator in 18-gallon cylinder.

Full-length (30 in.) element, loading 2·5 kW, shown thus ———
Lower-third (12 in.) element, loading 2·5 kW, shown thus — — —
Thermostat 18 in. long set at 150° in both cases.

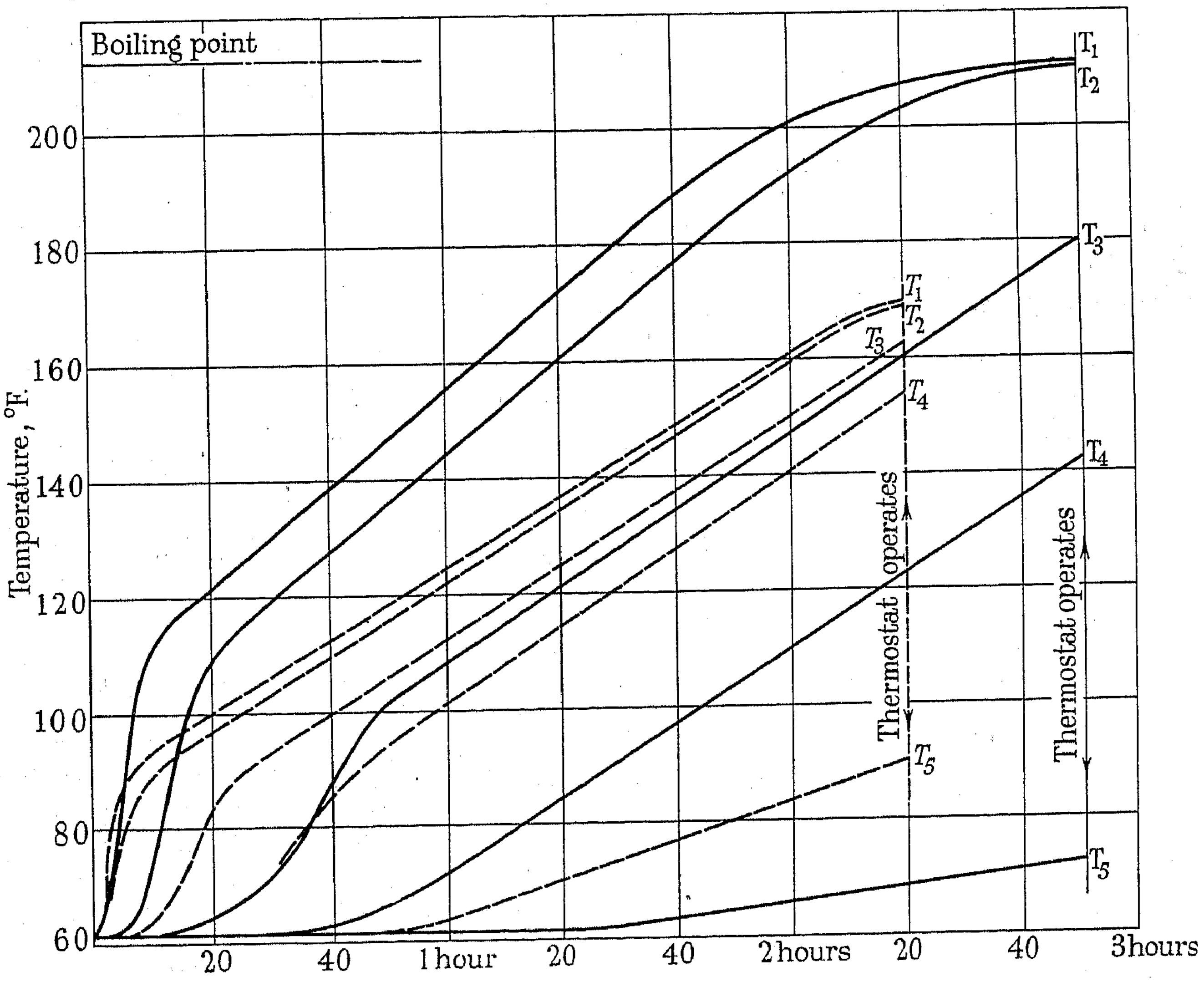


Fig. 6B.—Heating curves for various circulators (for key to T_1, T_2, etc., see Fig. 6A).

Immersion heaters were originally fitted horizontally at the side of a storage tank, and when they are used in this way the whole of the water above the level of the element has to be heated before hot water is available. This is not a serious disadvantage when a thermostat is fitted to control the immersion heater so that the water is always kept hot, but as many users were unwilling to incur the extra expense of a thermostat and the lagging of the tank which is required to give a reasonable operating cost, it became evident that there was a field for another type of heater which would give quicker results when starting from cold. The alternative arrangement, which was soon evolved and has since been used in large numbers, is the "circulator." This consists of an immersion heater fitted vertically downwards from the top of the storage tank or cylinder, the heating element being surrounded by an outer sheath or draught tube, and the water in contact with the element circulating upwards and emerging through a hole at the top of the tube. The size of the hole is restricted so that the water flowing out of it is raised to a usable temperature. By careful proportioning of the length and diameter of the draught tube to suit the size and loading (usually 3 kW) of the element, a small quantity of hot water can be furnished within a few minutes of switching on the current. Circulators of this type have attained great popularity, particularly in soft-water districts where copper cylinders are used. A circulator can be fitted to such a cylinder very easily by means of special flanges designed to make a water-tight joint in the top of the cylinder by the mere process of cutting a circular hole. Standard shapes of copper cylinder have a height much greater than their diameter, so that hot water is readily accumulated at the top of the cylinder by the circulating action. The circulation is improved if the flange is designed so that the circulator is in a truly vertical position rather than the slightly diagonal position which results from it being fitted at right angles to the curve of a domed top.

As, however, the copper cylinders fitted in some houses are so small that the whole of the contents must be heated in order to obtain a hot bath, the recent trend in circulator design has been towards ensuring both quick and complete heating. With a simple type of circulator these two objectives are to a certain extent incompatible. Figs. 6A and 6B show, for example, the results of tests on two similar circulators—one with an element in which the heating effect is uniform throughout its length in order to give quick heating-up, and the other with the heating effect confined to the bottom third of the length, in order to heat the water in the lower part of the cylinder to a higher temperature. Improved designs such as those shown in Fig. 7 are now available by which quick heating and maximum output are obtained.

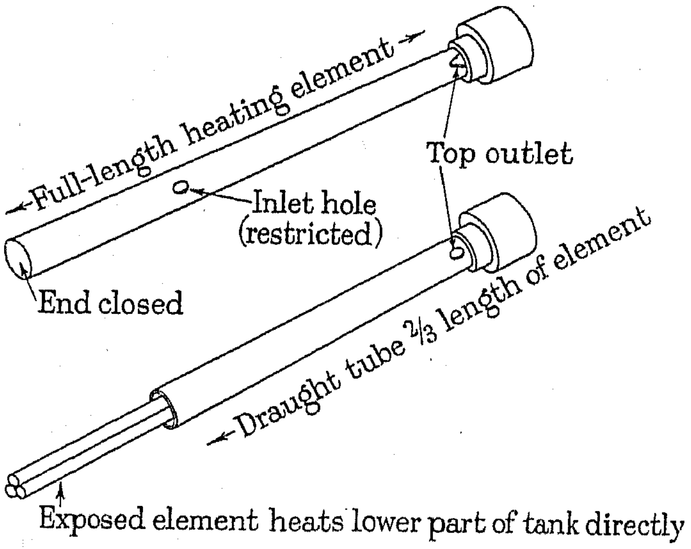

Full-length heating element
Top outlet
Inlet hole (restricted)
End closed
Draught tube ⅔ length of element
Exposed element heats lower part of tank directly

Fig. 7.—Special designs of circulator giving maximum storage plus quick heating.

A further development in design is the two-way circulator in which there are two elements, one wound in the upper third of the length of the circulator and connected to the supply under thermostatic control so as to keep the water in the top of the tank constantly hot for domestic purposes, the other element being wound over the lower part of the circulator and switched on by hand whenever the full contents of the tank are required for hot baths.

In hard-water districts, circulators are seldom used because of the liability of scale blocking up the draught tube. A vertical arrangement of the heating element will, however, give a quick heating effect similar to that in a circulator because the film of water in contact with the heating-element surface rises by convection much more rapidly than heat is transferred radially by conduction. Fig. 8 shows this action diagrammatically, and the effect is confirmed by tests which indicate that removing the draught tube of a circulator only increases the heating time by 10 % to 15 %, depending on the heat density of the element. Vertical elements must, however, be carefully designed for use in hard-water districts, because, even though the heating effect is tapered from bottom to top of the element, there is a tendency towards overheating at the top of the element, owing to the rise in temperature of the film of water as it flows up the heater. Unless the tank is so large that a low operating temperature (130°–140° F.) can be used and an element of low heat density (10 watts per sq. in. or less) employed, it may be better for very hard water to fit two horizontal immersion heaters, one near the top for quick heating and the other at the bottom to heat the full contents of the tank.

Lagging for Existing Tanks and Cylinders

Specially manufactured insulating jackets are available for lagging existing tanks and cylinders. These are usually made up with asbestos or cork insulation arranged in strips or in some other form so that they can be applied to various sizes and shapes of cylinder. In this way the loss from a 36 in. × 14 in. diameter cylinder may be reduced from over 10 kWh to less than 3 kWh per 24 hours. The highest efficiency is obtained when the number of joints is reduced to a minimum, since it is often difficult to fit these on site so that no gaps are left in which air convection can increase the heat loss. On account of this difficulty and to save expense, other forms of lagging made up on site are commonly used, especially for rectangular tanks. The latter are usually situated in the bottom of a linen cupboard, in which case the simplest plan is to fix match boarding across the front of the cupboard and then to fill the space around and over the top of the tank with loose granulated cork. If in this way a minimum thickness of 3 in. of cork can be provided, the loss is reduced to a low figure, say 2 kWh per 24 hours. For cylinders it is not quite so easy to improvise cork lagging in this way; an alternative that is sometimes adopted is to wind a sheet of asbestos and several thicknesses of corrugated paper round the cylinder and, if possible, to enclose the whole in a stout canvas jacket. The above figures for heat loss from lagged tanks represent reasonably good practice, all incidental losses due to radiation from and conduction to connecting pipes, etc., being included.

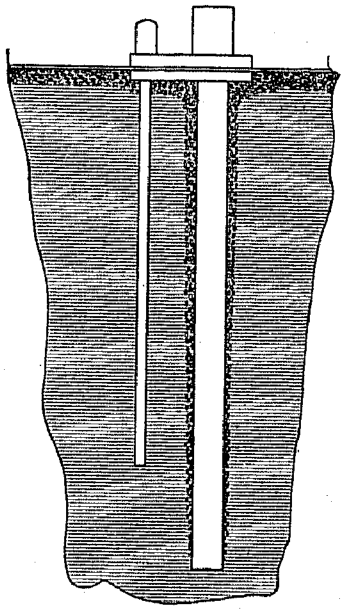


Fig. 8.—Film of hot water flowing up vertical element.

The heat loss from the tank surface alone and without lagging is generally taken as 0·6 watt per sq. ft. per deg. F. difference in temperature, i.e. 72 watts per sq. ft. for air and water temperatures of 60° and 180° F. respectively. When the tank is well lagged with 3 in. of good-quality granulated cork, the surface loss may be as low as 4 watts per sq. ft. Taking this figure, for a 20-gallon tank consisting of an 18-in. cube (surface 13·5 sq. ft.) the loss will be 54 watts. The difference between this surface loss and the total of 83 watts which corresponds to a consumption of 2 kWh per day is attributable to incidental losses due to such factors as radiation from, and conduction to, connecting pipes.

Sometimes the efficiency of a tank lagging is expressed in terms of the rate of cooling which is observed when no water is drawn off and no energy applied. Provided that the cooling rate is measured for temperatures very close to the maximum, the relation between this rate and the loss in watts, as measured by the energy consumed in keeping the tank hot, depends upon the capacity of the tank. Thus if a tank of G gallons has a loss of P watts and a fall in temperature from the maximum of θ degrees in 1 hour, then we have

$$P = 10G\theta/3{\cdot}41 = 2{\cdot}93G\theta$$

and

$$\theta = 0{\cdot}341P/G$$

This relation is shown in Fig. 9.

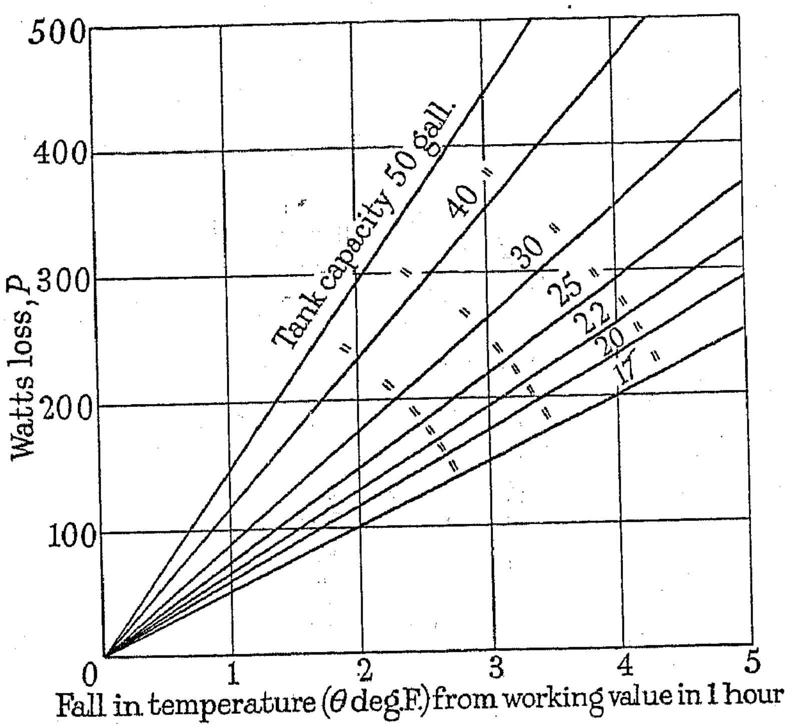


Fig. 9.—Relation between radiation loss and cooling of tanks ($P = 2{\cdot}93G\theta$).

The advisability of lagging tanks and cylinders when fitted with immersion heaters or circulators, is a question on which opinion is inclined to be sharply divided. There is no doubt that if efficient insulation is applied, as it can be in the majority of cases, and the electric heating installation is operated so as to give constant hot water under thermostatic control, its general utility and convenience are greatly enhanced. On the other hand, those who do not believe in lagging take the view that the radiation losses, together with the increased consumption of hot water which naturally follows from greater availability, can result in unduly high operating cost.

The author maintains that there is a field for both lagged and unlagged types of installation, depending upon the amount of hot water required and what the user can afford to pay for it. In other words, the unlagged installation operating under hand control is suitable for working-class consumers, but more well-to-do consumers should be provided with lagged automatic systems which enable them to obtain the full advantages of electric water heating.

Borderline Cases

In cases where there may be some doubt as to the user wishing to afford constant hot water, a switch can be fitted in circuit with a thermostatically controlled circulator so that users can at first control the heating by hand, and later, when they find that the cost of keeping the water hot continuously is not excessive, they will not bother to switch off. In such installations it is an excellent plan to have a small notice fixed to the heater stating that the thermostat will turn the current off automatically, and that very little electricity, for example a pennyworth per day, is required to keep the tank hot if no water is used.

Where there is less likelihood of constant hot water being afforded at all taps, a good compromise is the provision of a 1½-gallon automatic heater for kitchen use, and a hand-controlled immersion heater or circulator to be used for baths as required.

Linen Cupboards

A further objection which is sometimes made to lagging, in cases where the tank or cylinder is situated in a linen cupboard, is that there will be insufficient heat for airing purposes. In regard to this it may be pointed out that no matter how well lagging is applied some loss of heat is inevitable, also that this heat loss, although small, is steadily maintained throughout the 24 hours of the day and may therefore be more valuable for airing purposes than the intermittent radiation from a bare cylinder heated by a fire-back boiler. For example, if 10 lb. of linen or clothes are put in the cupboard to air they may contain ¼ lb. of moisture, depending upon the prevailing humidity in the atmosphere. Removal of this amount of moisture, requiring 512 B.Th.U. or 0·15 kWh, can be readily effected by a lagged tank having a loss of, say, 2 kWh per day. These considerations are perfectly correct as regards the airing of clothes, but they do not of course apply to clothes-drying, which requires a much greater amount of heat, and for which a closed cupboard is in any case unsuitable. Washed clothes should be dried in a drying cabinet or other type of drying arrangement heated electrically as required.

If, on the other hand, some means of drying wet towels after use is required, it is better to install an electrically heated towel-rail in a convenient position in the bathroom. Electric towel rails have approximately the same heat input as those heated by hot water, i.e. 100 to 200 watts, and, since the ordinary bath towel when damp may not require more than 0·1 kWh to dry it, an electric towel-rail need only be used for a very short time. This method of drying wet towels is much more economical than omitting some of the insulation from an electrically heated tank.

INSTALLATION PRACTICE

General

There is no doubt that the installing of a self-contained electric water heater, an immersion heater, or a circulator, involves almost as many if not more problems than the manufacture of the apparatus.

Water heating is unique among the various applications of electricity in that it calls for expert technique including as much hot-water engineering knowledge as electrical knowledge. In most small houses, which, of course, include the majority of potential users, there is seldom any serious difficulty, but in large houses the hot-water pipework is frequently complicated either because it was installed many years ago or because there is a central heating system operating in conjunction with it, and in such cases electric heating to be successful can only be installed with due attention to the existing installation and the best method of applying electric heating to it.

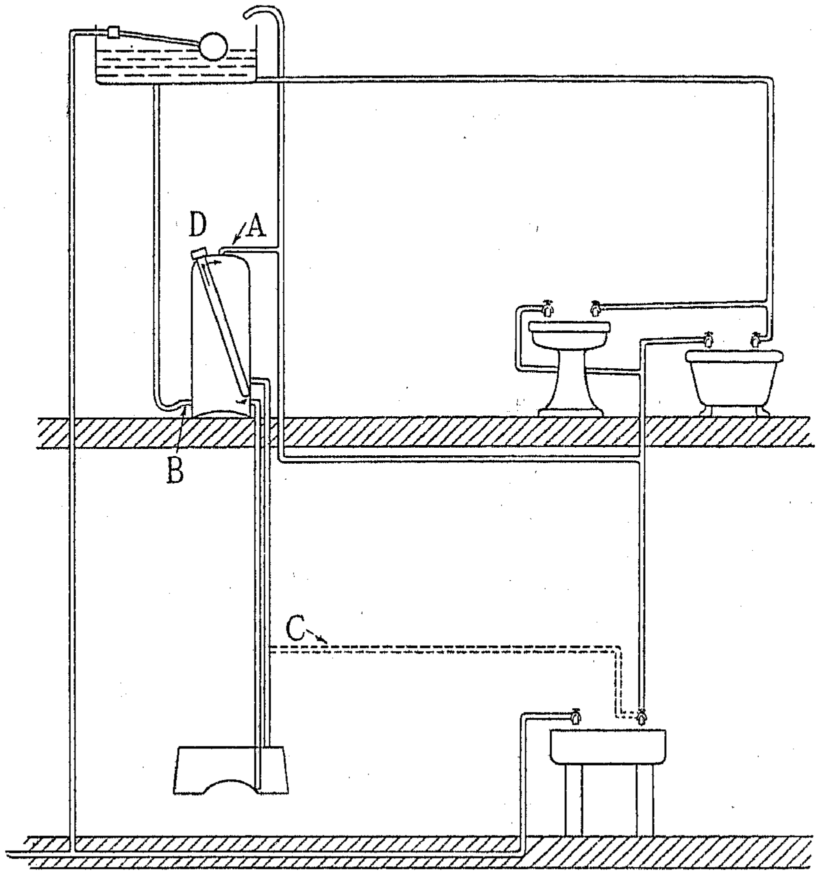


Fig. 10.—Typical system in a small house, converted to electric heating by a circulator in the cylinder.

A. Horizontal length (at least 12 in.) of pipe forming "heat trap."
B. If cold feed does not enter horizontally but from underneath, a T-piece should be fitted inside the cylinder to prevent undue mixing.
C. This alternative connection must be altered for electric heating.

The chief objects to be secured are:—

(i) Safety from danger of bursting. This is ensured either by an open outlet or by an expansion pipe.

(ii) Minimum practicable heat losses. These include not only the loss from the water heater itself, but also heat losses from pipes, which may be more important if steps are not taken to reduce them to a minimum.

(iii) Correct piping connections, which will ensure a good flow of water and will prevent the electric water heater from being accidentally drained.

These and other points which arise from a water-engineering point of view are best illustrated diagrammatically. Fig. 10 shows an existing hot-water installation using a cylinder in an ordinary small house, the water being heated by a fire-back or independent boiler. On account of the simplicity of such an installation, and also because it enables electric heating to be used in the summer time, the solid-fuel heating being relied upon in the coldest months, an immersion heater or circulator is very commonly employed as illustrated in Fig. 10. This Figure also shows some of the unsatisfactory features of the installation which should be altered in order to obtain the best results with electric heating. The chief point to note is the connection to the hot tap in the kitchen. It used to be common practice, particularly in the South of England, to supply this tap from the boiler flow pipe so that hot water could be obtained from it as soon as possible after lighting the fire. If an electric heater is to be fitted to the cylinder this practice must be abandoned, and the connection made to the top of the storage tank, to enable hot water to be obtained from the kitchen tap when the boiler is not in use.

The principal points to be observed in connection with self-contained heaters are that a pressure-type heater must be fitted with its own expansion pipe and that cistern-type heaters must be fitted above the level of the taps to be supplied. The actual position in which the heater is fixed often depends upon the space available in a particular house. A pressure-type heater should preferably be fitted in the kitchen or immediately overhead in such a position that the most frequently used pipe, i.e. that to the kitchen sink, may be as short as possible.

Pipe Losses

Loss of heat in pipes is due to (i) the heat absorbed by the metal, (ii) the radiation and convection loss in the pipe if kept hot, and (iii) the heat stored in the water content if it is allowed to become cold (" dead " water). An approximate comparison between the magnitudes of these losses per 10 ft. of $\frac{3}{4}$-in. iron pipe at 180° F. is: (i) 63 watt-hours, (ii) 200 watts, (iii) 75 watt-hours. From this it will be seen that the radiation and convection loss is considerable if the pipe is kept hot continuously, and it is therefore essential when electric heating is used that the greatest care should be taken to reduce such losses to the minimum. Circulating loops in hot-water pipework should be cut out or shut off; one of these alterations is usually possible in private houses without unduly lengthening the time taken for hot water to flow from the distant taps. In other cases, particularly for any distant tap which is in frequent use, the installation of a separate local heater should be considered. In large installations, e.g. for a central system feeding a block of flats, a circulating or 2-pipe layout may be essential but in such cases the circulating pipes should be lagged with best-quality lagging having an efficiency of at least 80 %. The loss from iron pipes run horizontally is approximately 19 watts per sq. ft. of surface for 100 deg. F. temperature-difference. When the pipes are lagged, the loss is reduced to about one-fifth of this amount, the values for typical sizes being given in Table 5.

For copper pipes, either left bright or chromium-plated, the loss will be about 60 % of that for iron, owing to the reduced radiation from a polished surface; but when the pipes are lagged the loss will of course be the same as for iron pipes.

In a private-house installation, care should be taken to prevent any appreciable length of pipe being kept hot continuously by internal circulation. Apart from circulating loops, which, as already mentioned, should be cut out when electric heating is used, the only pipe which may be kept hot is an expansion or flow pipe rising vertically from the top of the hot-water storage tank or cylinder. In order to prevent internal circulation in a pipe of this kind, a "heat trap" should preferably be formed. This is best done by carrying the pipe horizontally from the top of the tank for a distance of at least 1 ft., as shown in Fig. 10. This horizontal length is sufficient to prevent internal circulation and is generally preferred to a U-bend, which may, under some circumstances, cause an air lock. In this way the continuous pipe loss may be reduced to a very low figure, say 20 watts.

Table 5

HEAT LOSSES FROM INSULATED PIPES PER FOOT RUN

Bore of pipe	Watts loss	Energy lost per 24 hours
in.		kWh
½	2·9	0·07
¾	3·5	0·085
1	4·0	0·096
1¼	5·0	0·12
1½	5·5	0·132
2	6·7	0·161
2½	7·9	0·19
3	9·6	0·23

In ordinary draw-off pipes which are only heated when water is drawn, lagging will only lengthen the time taken for the pipe to become cold. In practice, effective lagging can seldom be applied to existing pipes, and in ordinary use water is drawn off infrequently, especially from bathroom taps, and so greater economy can be obtained by reducing the amount of heat absorbed by the pipe and its water content. In this respect copper pipes have a marked advantage over iron, as will be seen from Table 6.

Table 6

HEAT (IN WATT-HOURS) STORED PER FOOT OF PIPE (AT 180° F.)

Bore of pipe	In water content	In iron pipe	In copper pipe (No. 18 S.W.G.)
in.			
½	3·0	4·4	1·1
¾	7·5	6·3	1·7
1	13·0	8·8	2·2

As a more practical illustration of the superiority of copper pipes, the following figures are of interest, giving the quantity of water at 150° F. which must be drawn through 15-ft. lengths of pipe, originally cold (60° F.), before the temperature of the water flowing out reaches 150° F.: Iron (¾ in.), 20 pints; copper (¾ in.), 8 pints; copper (½ in.), 6 pints.

Another advantage of copper pipes is that owing to their smooth bore and to the fact that they can be installed with easy bends which offer less obstruction than sharp elbows, the flow of water is better, with the result that ½-in. copper piping can be used instead of ¾-in. iron pipe.

The heat loss from pipes due to water being drawn off is hardly susceptible to exact estimation, owing to the indefinite cycles of use. The simplest method of approximation for unlagged pipes, which lose their heat fairly rapidly, is to assume that all the heat is wasted, with the result that the loss can be expressed as the energy stored in pipe and water per draw-off. Suppose, for example, there are 10 draw-off periods at a kitchen tap supplied by a 15-ft. length of ¾-in. iron pipe; from Table 6 the total loss will be:—

$$10 \times 15 \times (7{\cdot}5 + 6{\cdot}3) = 2{\cdot}07 \text{ kWh}$$

As the daily loss from a separate 1½-gallon heater fixed at the sink would be only, say, 0·5 kWh, and as the capital charges or the hire charge of such a heater may be no more than ½d. per day, which is equivalent to, say, 1 kWh, it will be more economical to install a separate water heater in the kitchen. It is, in fact, an accepted rule that in cases where the length of hot pipe to the kitchen tap is in excess of 15 ft. the installation of a local heater should be considered.

Referring to bathroom taps, the less frequent use is to some extent counterbalanced by the larger size of pipe commonly used, and the generally accepted figure at which the installation of a local water heater should be considered is 25 ft. In practice, of course, such considerations have to be weighed in conjunction with other factors such as space available, cost of energy, position of pipes, and so on.

Larger Installations

Fig. 11 illustrates the conversion of a more extensive installation by using different types of self-contained electric water heaters. A cistern-type heater is used to supply two sinks on the ground floor, and separate pressure-type heaters are employed for the bathrooms on the first and second floors. The use of three separate local heaters is the maximum amount of decentralization which can be carried out to reduce pipe losses. A decision as to whether this would be desirable in any particular case would depend upon the distances between the various points to be supplied, and upon whether space could be found for the local heaters. If the bathrooms are far apart, the arrangement shown is certainly the best that can be adopted for a new house. It has only one disadvantage, namely the fact that there is no pooling of storage capacity to guard against unusual or emergency requirements for hot water. On this account, as well as because of the greater simplicity of an installation of this kind, many hot-water systems in existing houses are converted by using one central tank. This may be either a large self-contained electric water heater, or the existing calorifier used for the indirect heating of a domestic hot-water supply from a central heating system. Although such calorifiers, as shown in Fig. 11, contain an annular heating cylinder or coil, space can usually be found for the fitting of an immersion heater and thermostat which, in conjunction with efficient lagging, enable electricity to be used from April to October when the central heating system is not in commission. Alternatively, when either the space-heating or the hot-water supply system is to be extended, conversions of this kind can be carried out instead of adding a larger fuel-fired boiler at much greater expense.

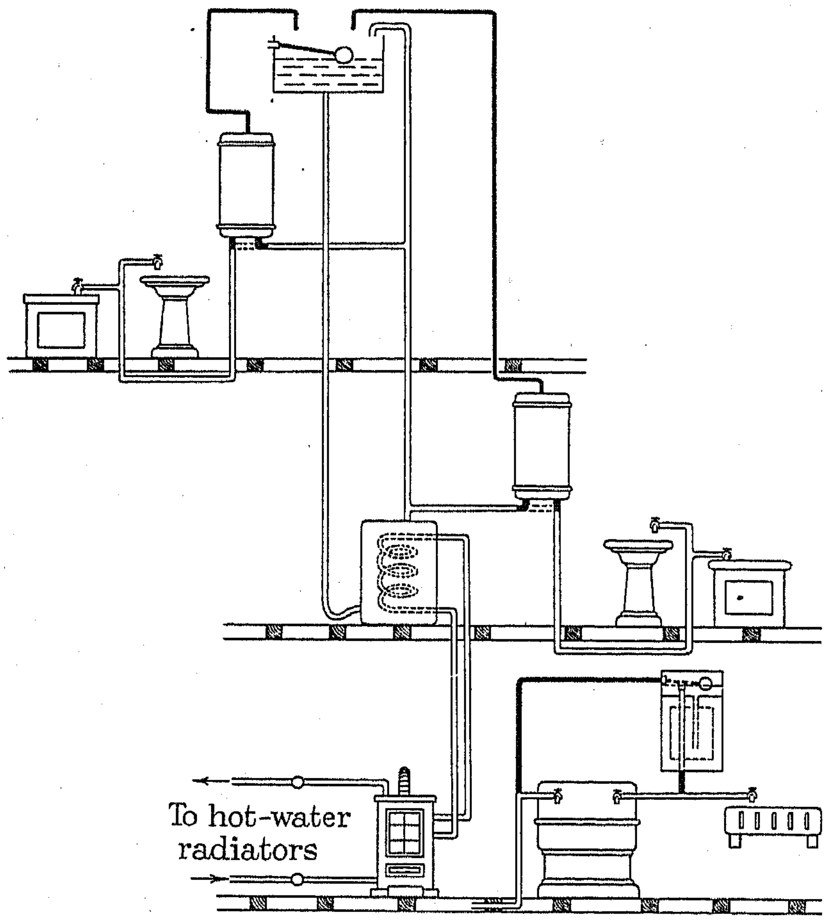


Fig. 11.—More extensive system using self-contained heaters.

New piping ━━━
Old piping used ═══
Old piping cut out ┅┅┅

Designs for New Houses

There is a considerable field for the application of self-contained heaters in the equipment of new houses, where the capital cost of the heater is offset by savings made on tanks and pipework which would otherwise be installed. Fig. 12 shows a simple installation for a small house in which a cistern-type water heater replaces the ordinary ball-valve tank, hot-water tank, and fuel-fired boiler. The layout of cold-water pipes shown would not be approved by water authorities who require the cold taps in the bathroom to be fed from a ball-valve tank, but the simple arrangement indicated is quite satisfactory for those districts where it is permitted. It should be noted that the heat loss from " dead " water in the pipe to the kitchen tap is reduced to a minimum by the use of $\frac{3}{8}$-in. copper pipe, which may have a total water content as small as $\frac{1}{3}$ pint.

For new houses of larger size in which a fuel-fired boiler is regarded as essential for space heating in addition to hot-water supply in the winter time, a special type of self-contained water heater fitted with boiler flow and return pipes may be used. If in addition care is taken to arrange the shortest possible pipe-run and to use light-gauge copper piping, the highest efficiency will be obtained and a smaller-size fuel-fired boiler can be installed, with a saving in the winter fuel as well as in the electricity bill.

Blocks of Flats

The provision of electric water heating in blocks of flats is a more complex problem. In the cheaper classes of flat where no central system is provided for space heating, each flat can be treated separately as though it were a private house. The only difference is that there is greater difficulty in accommodating the water heater in a flat, and for this reason made-to-measure heaters are often installed, designed to fit in cupboards or under the ceiling of the hall. For better-class flats, particularly those in which a charge for " constant hot water " is included in the rent, the problem is more difficult, but a number of very successful installations of the central-storage night-tariff type have been in use for some years in various parts of London. In these cases central storage tanks solve the problem of the great variation in use of hot water that occurs in individual flats. A storage of 80 to 100 gallons per flat will be usually sufficient to meet the demand throughout the day, say from 7 a.m. to 10 p.m. With this type of installation, energy is supplied under time-switch control during the night at a rate per kWh of approximately

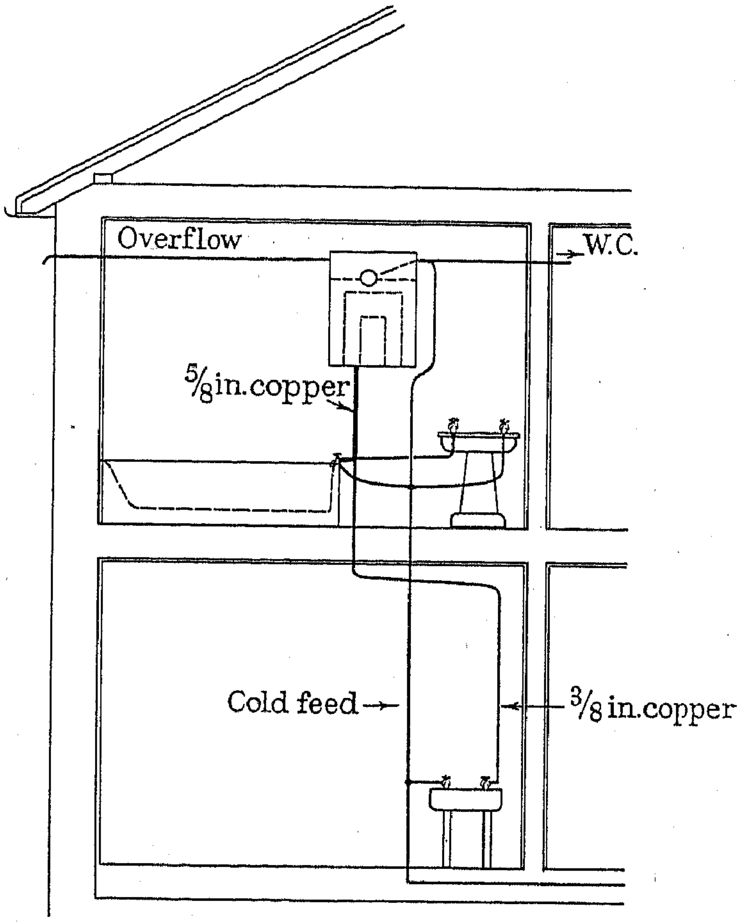


Fig. 12.—Simple cistern-type heater installation in small house.

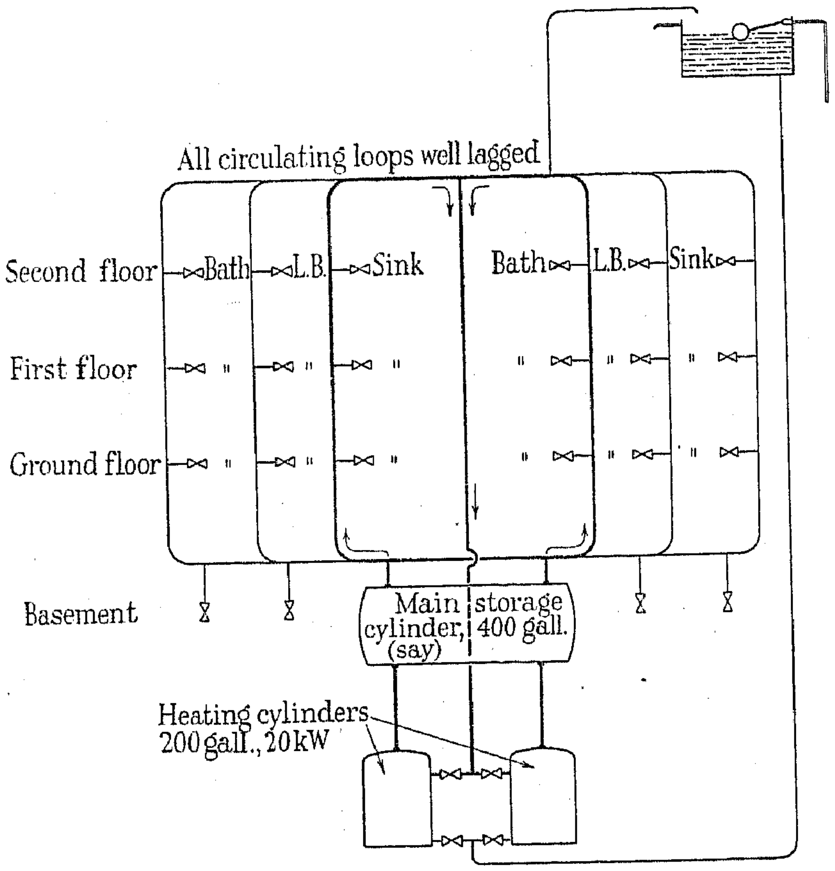

All circulating loops well lagged
Second floor
Bath
L.B.
Sink
Bath
L.B.
Sink
First floor
Ground floor
Basement
Main storage cylinder, (say) 400 gall.
Heating cylinders 200 gall., 20kW

Fig. 13.—Schematic pipework diagram of large central-storage system.

two-thirds that obtainable under ordinary tariffs. The lower energy cost enables the large amount of hot water to be provided more economically and also reduces the cost of the heat losses from the circulating-pipe system which is essential for this type of installation, a typical schematic pipework diagram of which is shown in Fig. 13.

The decision as between a local and a central system in any particular case depends chiefly upon commercial considerations. If the tenants have to pay their own bills for hot water, local heaters must be employed. On the other hand, if the landlord pays for the hot water, a central system is more likely to give satisfaction because the exceptionally large quantities used by some tenants when they do not have to pay according to quantity, make it almost essential to use central storage in order to take advantage of the diversity between the habits of different users. A central system is bound to be less efficient than local heaters, because of the radiation loss from circulating pipes, but the lower efficiency is more than counterbalanced by the reduced cost per kWh which applies when a central system is supplied on a night tariff and the local heaters on ordinary tariffs.

Fig. 14 shows typical consumptions in various kinds of flats.

Commercial Premises

In addition to private houses and flats, there is a considerable scope for electric water heating in commercial premises, e.g. hairdressers' and other shops, and offices and factories. Installations of this kind can be readily designed using the types of apparatus already described, isolated groups of wash hand basins each having their local storage in a self-contained water heater or converted tank. Typical hot-water consumptions and storage capacities for various classes of premises are given in Table 7. These figures, which are based on the experience of electrically heated installations, are lower than those usually allowed by heating engineers in designing fuel-fired systems, the reasons for this being first the absence of heavy pipe losses when electric water heaters are used, and secondly that heating engineers' allowances appear to include a margin for variations in boiler-flow temperature.

Table 7

ELECTRIC HOT-WATER SERVICE IN COMMERCIAL PREMISES

Type of building	Consumption (kWh)	Gallons storage (at 160° F.)	Remarks
Lavatories in public conveniences, hotels and restaurants	¼–½ per wash	2–5 per basin	For wash hand basins, especially those in unattended lavatories, spring taps are advisable and may save as much as 30 % in operating cost
Lavatories in factories	1–2 per head per week	½–1 per head	
Lavatories in offices (including cleaning)	2–3 per head per week	½–1 per head	
Shops (hairdressers')	7–20 per basin per week	3–5 per basin	Consumption depends on number of shampoos
Shops (butchers' and fishmongers') ..	15–20 per week	12	
Shops (snack bars)	15–30 per week	1½–5	Consumption depends on size and hours of opening
Surgeries (doctors' and dentists') ..	7–10 per week	1½	
Clubs, sports pavilions	2–3 per shower	8–10 per person, neglecting recuperation	Consumption applies to ordinary showers; if special electric shower heater used, consumption is less (say 1·5 kWh)

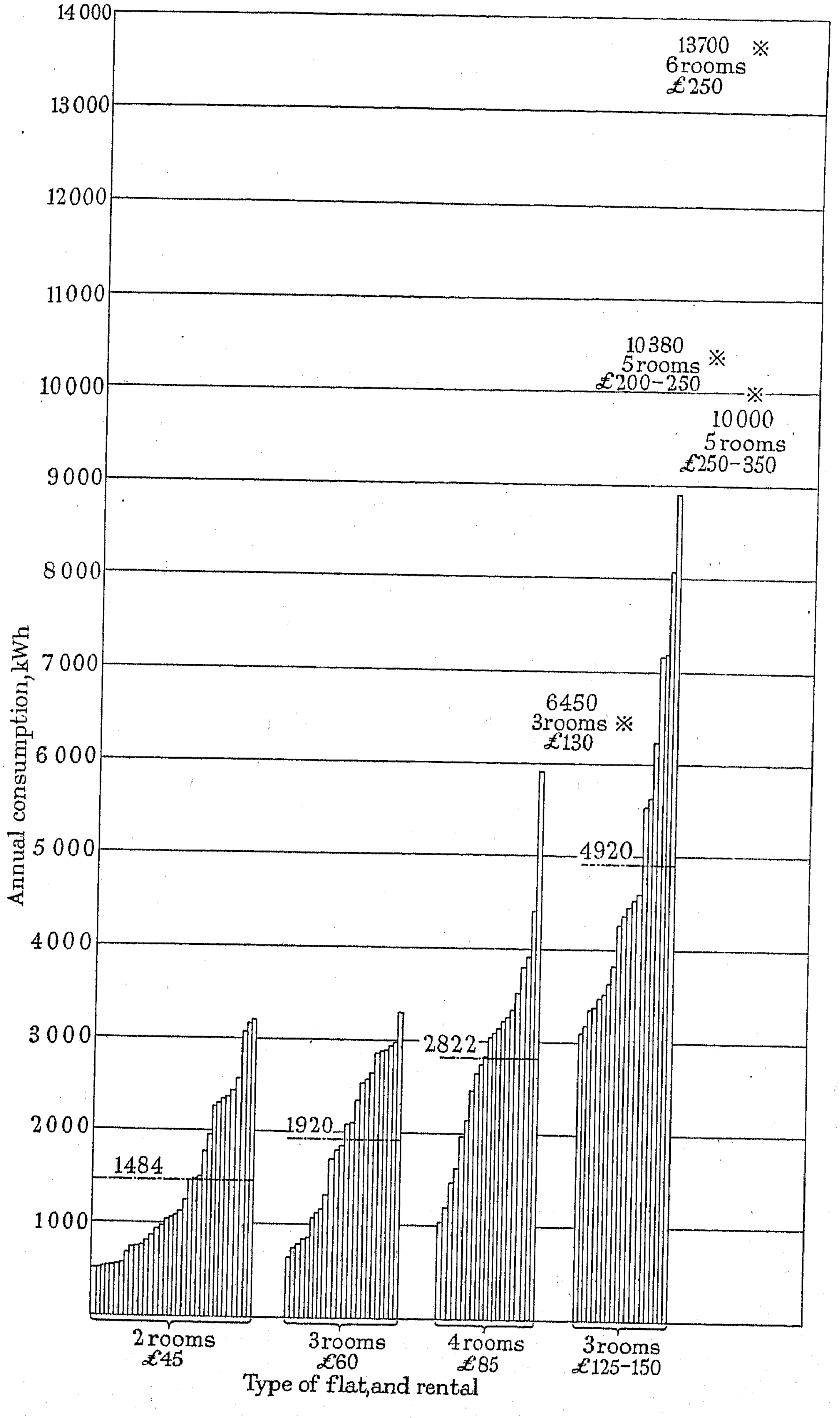
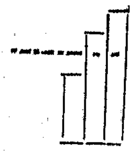


Fig. 14.—Consumption of electricity for water heating in blocks of flats in London.



Average

Local heaters: hot water at tenant's expense.

※ Central (night storage) heaters: hot water included in rent. Average consumption per flat.

Water Authorities' Regulations

Since the installation aspect of electric water heating is so important, reference must be made to the various requirements of water supply undertakings. These vary widely, despite the model form issued by the Ministry of Health, special regulations of individual undertakings being justified presumably by variation in the composition of the water supply or in the reservoir and mains system.

Generally speaking, water undertakings are concerned with the following objects:—

(i) To ensure purity of the water supply. This does not affect consumers' installations except in the case of those water authorities which require for this purpose that all electric water heaters of over 3 gallons capacity shall be supplied through a ball-valve tank or by a broken-feed arrangement which will prevent the water contained in the heater from draining back into the mains in the event of the supply failing. The alternative safeguard of a non-return valve in the feed pipe is not usually regarded as sufficiently reliable.

(ii) To prevent waste. This is achieved *inter alia* by a requirement that all taps and ball valves shall be of approved design; the majority of water undertakings accept those made to a rigid specification sponsored by the British Waterworks Association, which are known as J.C.S.W.R. fittings.

Bursting or flooding, which, in addition to being a source of waste, may cause damage to consumers' property, is taken care of by regulations requiring expansion and overflow pipes to be installed, the latter in such a position that a discharge of water will be clearly visible.

A further regulation which has been adopted by some water undertakings and is intended to prevent waste, is a limitation of the length of hot-water draw-off pipes with a view to reducing the amount of dead water.

Some water undertakings are also concerned:—

(iii) To reduce consumers' maximum demands. This applies particularly in areas such as London where house service pipes may be rather small for the increased water consumption of the present day, and results in regulations limiting the size of electric water heaters supplied direct from the main to a capacity of 3 gallons.

Wiring Installations

The electrical connections to electric water heaters do not call for special comment, except in relation to the following points:—

(i) Self-contained heaters, particularly those fitted in bathrooms, should be connected direct to a distribution fuseboard, the use of a plug and socket being avoided on account of the likelihood of the socket being used, on occasion, to supply other apparatus (such as a portable fire) which might give rise to serious danger of shock.

The risk of shock from an electric water heater itself, even when fixed in a bathroom, is very small in comparison with that associated with other appliances, because the water heater is invariably connected to the adjacent pipework by metal-to-metal joints; but, apart from this, the water heater should be earthed in the usual way, the connection being made to a suitable terminal on the apparatus plate, to which the outer metal case should be bonded internally.

(ii) The connections to water heaters should be made so that the thermostat is connected to the live pole of the supply, as this prevents the thermostat being short-circuited if an earth fault should occur in the heating element.

ELECTRICITY SUPPLY ASPECTS

Factors Affecting Policy

Just as there have been two main lines of development in the design of electric water-heating apparatus, namely the self-contained heater and the immersion heater, so electricity supply policies have been based on two different points of view; in fact, it might be said that the supply aspect has governed the design of apparatus.

The self-contained water heater, with its relatively low loading and high efficiency, was advocated originally on the Continent as the best means of filling the valleys of the load curve, and therefore justifying a specially low electricity tariff. In many towns on the Continent, practically all the electric water heating is still carried out at a low rate of between 50 % and 75 % of the rate for cooking and domestic power, energy being supplied only during the night. The other supply policy, which has been adopted in this country and in Canada, where electricity is supplied at very low rates for general domestic purposes, has been to recommend the simple immersion heater or circulator, often with hand control, on the ground that many more installations of this inexpensive kind would be installed and that the effect of the higher loading would be offset by increased diversity. In this country both schools of thought have had their adherents among supply engineers, but the consensus of opinion is that neither policy is correct for all cases and that in every town there are a certain number of consumers who require and can afford constant hot-water service, while the remainder, who are numerically in the great majority, can only afford the intermittent service obtained with hand-controlled immersion heaters or circulators. In dealing with individual cases experience is the best guide, and, as has been mentioned in the section on "Borderline cases," a compromise is often advisable.

It is difficult to define the dividing line between the two types of service. On the one hand, constant hot-water service will account for a greater use of hot water, and therefore a greater consumption of electricity, because of the constant availability of the hot water. On the other hand, the apparatus required for providing constant hot water is somewhat more expensive; and though the extra outlay can, for the same service, be saved in operating cost in a year or less, consumers may not appreciate its worth, especially if electric water heating is still regarded as a new-fangled idea to be approached with great caution.

As regards the value to the supply authority of the load provided by different types of water-heating installations, there is scope for further study. Broadly speaking, all the domestic water heating in this country is supplied at the running rate of the ordinary two-part tariff. In urban districts this is usually in the neighbourhood of ½d. per kWh, and this figure results in reasonable cost compared with other alternative methods, especially when electric heating is used in the summer and a solid-fuel-fired boiler in the winter. Typical average consumptions for different types of electric water heater are given in Table 8, it being understood that the actual consumptions in individual cases vary widely from the average values. From these figures it will be seen that the consumption of electricity for water heating is substantial, e.g. it is generally much larger than the consumption for cooking.

The value of the load to the supply authority depends on its demand characteristics as well as on the actual consumption, and the demand is so low and the consumption so high that water heating is the best of all domestic applications of electricity. As regards the actual demand or, expressed in another way, the diversity of the electric water-heating load, precise data relating to conditions in this country are difficult to obtain.

By far the most complete investigation of this aspect of the subject was carried out in the U.S.A. in 1930 by the Electric Water Heating Committee of the National Electric Light Association, the results being issued in N.E.L.A. Report No. 166. This covered a large number of field tests, using 70 simultaneously-recording ammeters to obtain the overall characteristics of groups of water heaters in different towns. Many of the results were only applicable to American conditions, but as the heaters tested varied widely in type—from 1-kW rating with thermostatic control to 6-kW hand-controlled heaters—it is possible to extract from the very extensive tests made a comparison between the heater loading and the average maximum demand after allowing for diversity, which is quite likely to hold good for British conditions. This comparison is shown in Fig. 15, from which it will be seen that the low-loaded heaters have the best load characteristics. Although this may seem self-evident, it is often disputed on the ground that the diversity of high-wattage elements will compensate for their greater individual demand; the N.E.L.A. tests showed the latter view to be partly correct when the water use was small, but when a reasonable amount of water was used the load curve became much more peaky.

Estimates made by the author of the average demands due to various types of water heater under British conditions are given in Table 8, and from these it is possible to calculate the cost of supplying the water-heating load if the demands shown are chargeable, i.e. if they add to the maximum demands on the distribution network or on the whole of the supply system. In many cases they will not do so, e.g. a circulator used only during the summer cannot affect peak loads occurring in the winter.

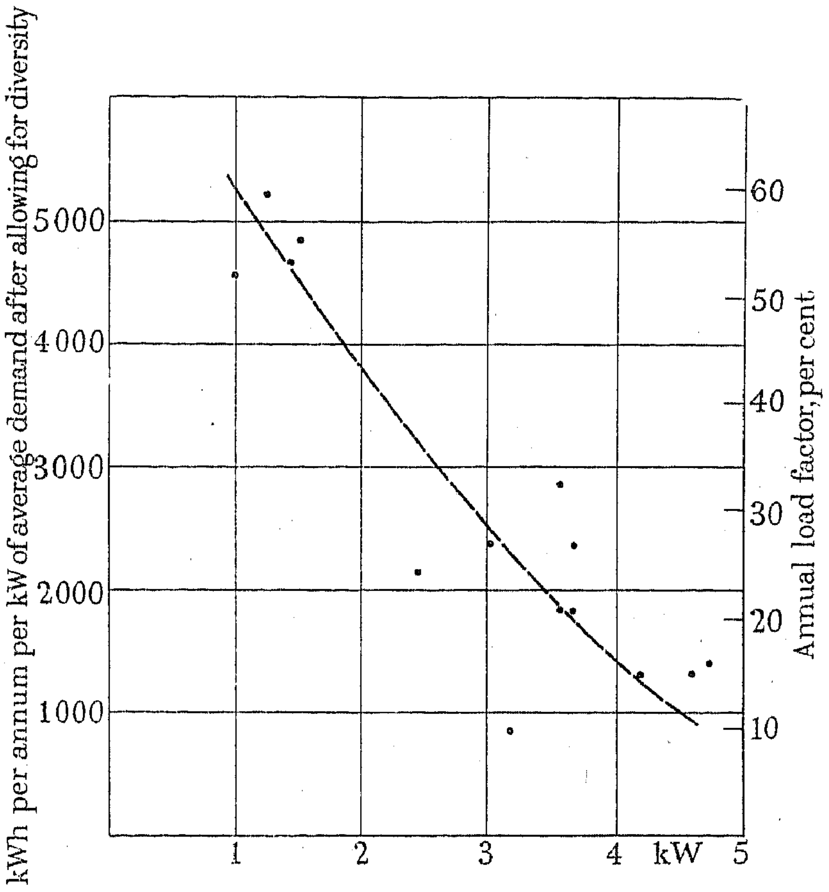


Fig. 15.—Relation between heater loading and load factor, after allowing for diversity (based on N.E.L.A. Water Heating Report).

Load Control

As regards 1½-gallon heaters or other heaters used all the year round, a simple method of preventing their load from being added to the cooking load in the individual house is to connect the water heater to a change-

Table 8

Load Characteristics

Type of water heater	Loading	Assumed energy consumption		Estimated average demand after diversity	Derived annual load factor	Remarks
		Per week	Per annum			
Self-contained—	kW	kWh	kWh	kW	%	
1½-gall.	0·75	17	900	0·4	26	All - the -year-round use
12-gall.	1·5	43	2 250	0·7	37	
15-gall.	1·5	58	3 000	0·75	45	
20-gall.	2·0	72	3 750	0·95	45	
30-gall.	3·0	86	4 500	1·25	41	
Circulator or immersion heater, hand-controlled	3·0	38	1 000	1·0	11	Summer 6 months only
Do., with thermostat	2·0	76	2 000	1·0	22	

over switch used for controlling the cooker. This can often be done without causing inconvenience to the user, but no tests appear to have been made to show the resulting effect on the network. If this method of load-levelling were at all costly to install, which it is not, doubt would probably arise as to its efficacy.

With regard to the future, it seems probable that greater attention will be paid in this country to more definite means of controlling the water-heating load so as to take advantage of its storage characteristics. The benefits to be obtained in this way may be applied either to the improvement of load factor with existing tariffs, or to enable lower tariffs to be quoted for the purpose of securing additional load not otherwise obtainable. Examples of the latter are large blocks of flats, and the provision of additional quantities of hot water for working-class houses and to meet competition from the more efficient alternative means of water heating. As has been noted above, some progress has already been made in this direction by offering for the night period a lower rate, under time-switch control, of, say, 0·3d. per kWh.

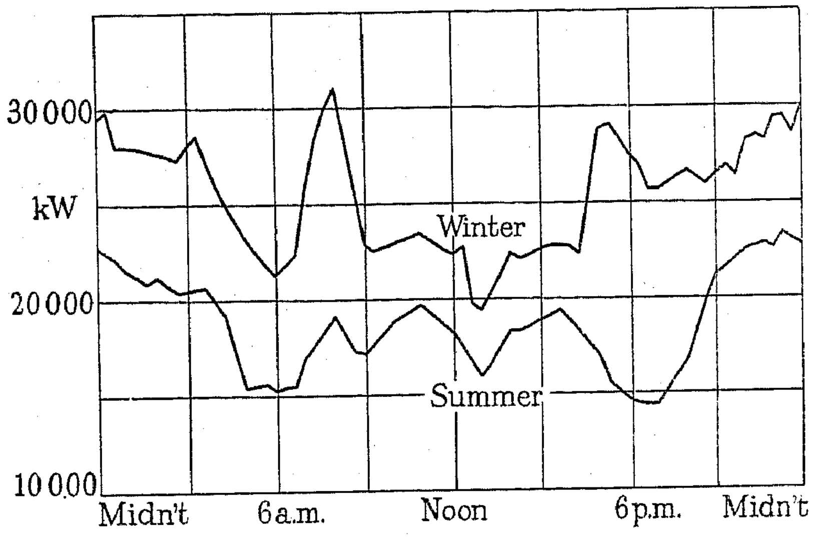


Fig. 16.—Winter and summer load curves for Basle.

The winter curve is that for 22nd December, 1937 (highest load of year), and the summer curve that for 21st July, 1937.

The improvement in load factor obtainable from controlled electric water heating may be illustrated by Fig. 16, showing winter and summer load curves for the supply undertaking in Basle, and Fig. 17, which indicates an impressive improvement in the load factor of this undertaking, largely due to electric water heating. There are now 20 391 electric water heaters in use in Basle, probably having a connected load in the neighbourhood of 25 000 kW, and yet the total system maximum demand for all classes of load is only 31 000 kW.

The policy adopted in the U.S.A. is also of interest. As electric water heating would be too costly for the user if energy were purchased at the ordinary domestic rates, some form of load control is regarded as essential, and in order to supply low-price energy profitably the hours of use are generally confined to the night—say from 11 p.m. to 7 a.m.—the rate per kWh being no more than 1 cent, which is comparable with $\frac{1}{2}$d. per kWh. The electric water heaters used are accordingly somewhat larger than those installed in this country, and furthermore, in order to enable extra heating to be used in the daytime, two elements are fitted. One of these is fixed at the bottom of the tank and is used to heat up the whole contents during the night. The other is fitted near the top of the tank and is used during the day as a booster, the energy consumed by day being charged at the ordinary date rate of, say, 2·5 cents per kWh. Each of the elements is usually controlled by a thermostat, and their loading is often limited in proportion to the capacity of the tank. Limiting the loading of the base-load heater ensures that current is supplied throughout most of the night, while restricting the booster loading prevents excessive demand during the day. As a result of extensive experience of users' requirements it is estimated that even in northern districts 35 % of the customers may be adequately served with 30-gallon tanks, and 50 % with 40-gallon tanks, the element loadings being between 500 and 1 000 watts.

As far as small and medium-sized houses in this country are concerned, there are two objections to a water heater which is only connected to the supply during the night, as in Continental practice. The first is that users are dissatisfied with a heater which gives only a limited amount of hot water and is incapable of giving any more until next morning. The second is that space for the larger capacity required is difficult to find in modern houses. So far no compromise has been found that will avoid these two objections.

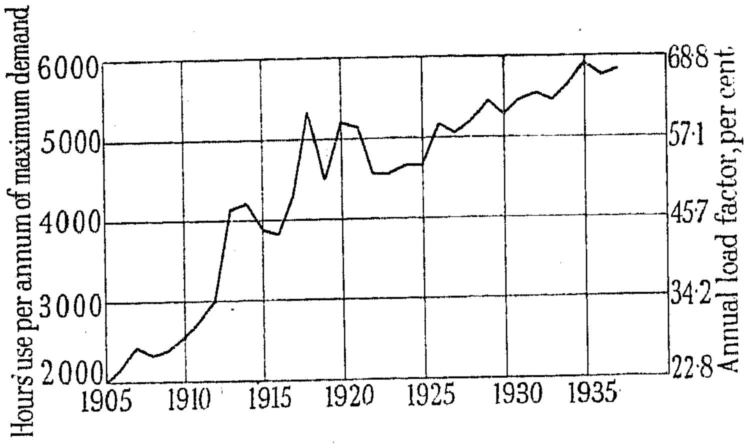


Fig. 17.—Improvement of load factor of Basle undertaking.

There is an alternative to the night tariff or 10-hour supply, namely the off-peak tariff by which energy is made available for 20 or 22 hours of the day, being only cut off at times of maximum demand on the system. This type of supply has been used to a slight extent, and might perhaps have received greater consideration if it were not for the fact that in many undertakings the time of the system peak has become increasingly uncertain with the extended use of electric cooking and space-heating. In a number of supply areas the peak load may now occur during any one of three periods of the day, namely breakfast time, 12 noon, and 4 to 6 p.m. If time switches are used to disconnect water heaters during each of these three periods of the day, there is a serious risk of users running short of hot water and being unable to obtain any more, unless the capacity of the water heaters is appreciably increased. The capital cost of this, together with the cost of the time switch and extra meter, and the additional accounting expense, are generally thought to make such a method of supply uneconomical. The position in regard to off-peak supplies of this kind has, however, undergone considerable change as a result of the introduction of practical systems of carrier-current control,* because by these means the whole of the thermal-storage load connected to the system can be controlled from a central point by a switchboard attendant who is aware of the total load on the system at every moment of the day. The difference between this and predetermined time-switch settings, which must necessarily include a substantial allowance for the occasional shifting of peak-load times, is very considerable. A rough estimate shows that the hours during which the supply is cut off during the winter months can be reduced from 250 to 50, or even less, if the thermal-storage load is a small proportion of the total system load.

Discussion of such methods of load control, involving extra cost for apparatus, is unnecessary for the many supply undertakings which have found by experience that electric water heating can be developed very satisfactorily on standard tariffs without restriction; but the lower cost of hot water to the user, or, alternatively, the improved load curve obtainable by means of a satisfactory form of off-peak control, is probably of interest in connection with the further development of the water-heating load or its commencement in undertakings with higher operating costs. The author would repeat, however, that electric water heating has already been developed in many parts of this country with a degree of success which is unequalled elsewhere, when allowance is made for the relative price of coal, and there is ample scope for further development on the lines which experience has shown to be satisfactory.

ACKNOWLEDGMENTS

The author desires to express grateful acknowledgment to those manufacturers whose products are described in the paper; he is particularly indebted to Aidas Electric, Ltd., Heatrae, Ltd., and the St. Marylebone Electricity Department, for information supplied, and to the Basle Electricity Works for data relating to that undertaking.

DISCUSSION BEFORE THE INSTITUTION, 5TH JANUARY, 1939

Mr. A. E. McKenzie: Sixteen years ago very few electric water heaters were made in this country, and those that were made were of the constant-trickle type, with a very low loading. We installed about 950 heaters of this type, but the great majority of them have been displaced by more modern types with higher loadings and, of course, better recuperation. To-day, British manufacturers are making excellent heaters of every type, and the British Standard Specification shortly to be issued will ensure even better heaters.

On page 2 of the paper, figures are given which show the percentage saturation in several countries. When comparing the domestic development of countries or towns it is very misleading to use the ratio of the number of pieces of apparatus to the number of consumers connected, instead of to the number of domestic premises in the area. The latter basis shows the possibilities of development, whereas the former does not. In the three towns supplied by the Wimbledon undertaking there are 38 000 domestic premises, 38 000 consumers taking electricity, and 17 633 electric water heaters. This gives 1 water heater for every 2·15 houses, or approximately 46·4 % saturation, which compares very favourably with the figures quoted in the paper. In addition, there are a large number of publicly-owned heaters.

I think that the figures given in Table 4 are actually the results of tests made at Wimbledon in 1932, when the loading of heaters of that size was 500 watts. To-day the loading is 750 watts, and of course very much better service can be obtained with that loading.

In Wimbledon, all self-contained water heaters are cleaned out once in 2 years, and 4 improvers are employed continuously on this work. All the heaters in a street are cleaned at the same time, thereby cutting maintenance costs down to a minimum. Taken over a period of years, the cost of cleaning such heaters, both large and small, averages 1d. per month. I am confident, however, that with increasing numbers this cost will fall in the future.

As the author states, the problem of scaling is more serious with the $1\frac{1}{2}$-gallon heaters than with those of larger capacity. Most of the scale is deposited at the top of the outlet pipe and at the anti-dripping device which is immediately over it. I have recently introduced a design which permits the removal for cleaning of the outlet pipe and the anti-dripping device without the necessity of removing any of the electrical connections or breaking the main apparatus plate joint. This enables the heater to be descaled and washed out in considerably less than half the time taken formerly, and of course at less than half the cost. It takes only a few minutes to carry out the operations necessary to remove the scale. Very little scale forms round the heating-element tube.

So far as immersion heaters are concerned, we have over 5 000 of the self-cleaning type installed and we have yet to experience a failure.

A strong case can be made out for the claim that the electric water heater is more reliable than any other type. Serious accidents due to electric water heaters are practically unknown. During the recent severe weather we were called on to attend to only 12 heaters, all of which functioned immediately the ice was melted in the supply pipes.

It is very much to be regretted that the Electricity Commissioners, when recently asked to grant longer periods than 7 years for the repayment of loans for the purchase of cookers and water heaters, thought fit to grant such extension for cooker loans only. My experience over the last 10 years with both cookers and water heaters indicates that the life of water heaters will be much greater than that of cookers.

There are two important details upon which the author has not touched. One is that spring-loaded taps or valves should be fitted to the basins of all public lavatories, in order to avoid waste of hot water. The second point is that captive jumpers should be fitted to all taps or valves where there is a restricted head.

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* Cf. H. Purslove Barker: "Centralized Control of Public Lighting and Off-Peak Loads by Superimposed Ripples," *Journal I.E.E.*, 1938, vol. 83, p. 823.

Under the heading " Load Control " the author refers to the practice of connecting the water heater to a change-over switch used for controlling a cooker, so that the two cannot be used simultaneously. Many engineers have not adopted this practice, believing that unsatisfactory water-heating would result; but for many years every cooker which we have installed has been fitted with a change-over switch, and we have more than 10 000 water heaters so connected and giving complete satisfaction. In most households a cooker is used at intervals for only 4 hours a day, and the remaining 20 hours is more than sufficient for water heating. During the past 10 years we have received on the average less than one complaint per year of insufficient heating. This practice of fitting change-over switches has saved the Wimbledon undertaking several thousands of pounds a year.

On undertakings where the domestic load predominates, it is uncertain when the maximum demand will occur, and therefore carrier-current control seems to be the only system for removing load at the peak periods. If we had been able to use such control for disconnecting radiators at peak periods during the recent cold spell, we should have saved many thousands of pounds.

Mr. O. W. Humphreys: In considering the author's estimate of the potential demand for electricity for water heating it is necessary to decide whether the assumption on which his estimate is based—that all consumers can afford to use electricity for this purpose—is sound. I think it is, at least during the summer months, provided the consumption of hot water can be properly adjusted in relation to the means of the user.

There is a danger that with the increased availability of hot water which results from the storage system, consumption may automatically increase, chiefly on account of the greater number of occasions on which the water is used. The author suggests countering this by using manual, instead of thermostatic, control, but as this means that the electric system is deprived of one of its most valuable features—immediate availability of hot water at all times—I feel that it would be better to try to educate the user to appreciate that hot water costs money, and to train him to use a continuously available supply with such attention to economy as his circumstances demand.

Mr. McKenzie referred to the British Standard Specification dealing with water heaters which is to be published shortly. I too believe that it will increase confidence in electric water heating, will stimulate the demand, and will be adopted by supply authorities which hitherto have of necessity had to prepare their own specifications. The specification is based on the sure foundation of the E.D.A. recommendations, which have stood the trial of a long period of use.

The author's reference on page 4 to the use of a calibration chart showing the relation between water temperature and thermostat setting, has, I think, been inspired by this Specification. The amount of heat available in a water heater of given capacity depends on the *mean* temperature of the water in the container, and this is a function not only of the thermostat setting but also of the design of the water heater, especially so far as it affects the temperature gradient between the top and bottom of the water in the container. If one takes, for example, a water heater in which there is a gradient of 25 deg. F. between top and bottom (this is not a commercial figure, but it can be obtained), and fits it with a short thermostat, occupying only a small proportion of the total height of the heater, the thermostat is naturally affected only by the temperature of the water immediately surrounding it, which is 10–15 deg. F. lower than the mean temperature of the water in the cylinder, and 15–20 deg. F. lower than the temperature of the water at the top of the cylinder. Clearly the amount of heat available in such a water heater is much greater than in one controlled by a thermostat having the same setting in which no such gradient exists. A way of overcoming this difficulty, which has been used in the past, is to employ thermostats specially set to suit the characteristics of the water heaters in which they are fitted, but this leads to confusion. The use of thermostats which are correctly set, and the provision, with each water heater, of a chart giving the relation between the thermostat setting and the mean water temperature, is to be preferred.

The author refers to the possibility of water boiling in water heaters owing to the use of a thermostat with too low a differential, but I think that the defect which he has in mind arises from very frequent withdrawals of small quantities of water rather than the thermostat differential. Under such conditions boiling may occur, especially in the case of bottom-entry water heaters fitted with long heating elements and short thermostats. The remedy is to be found in attention to details of design.

While I agree with the author that tinning of copper containers is unnecessary so far as health considerations are concerned, there are other considerations, such as the appearance of the inside of the container, and the copper staining of baths and basins in areas where the water is cupro-solvent, which may warrant the retention of tinning. The American practice of using monel metal for water-heater interiors is probably justifiable where water heaters are used on high-pressure water supplies and advantage can be taken of the greater strength of this material. In this country, pressure-type water heaters are not connected direct to water supply mains and it is therefore necessary to make sure, before adopting a more costly material than copper, that the advantages gained are sufficient to justify the added expense.

My final point is in connection with installation. I would suggest that we try to keep economy and convenience in their proper perspective. I agree that in the case of consumers who have to consider every penny of expenditure the water heater should be fixed as close as possible to the kitchen sink; but there are very many consumers who show by their normal mode of life that they value convenience at quite a high figure. In such cases I think that it is far better to put the water heater in the place which is most convenient, which will frequently be the one in which it is least conspicuous, rather than in the one which results in the greatest economy.

Mr. W. Millner: I should have liked to see in the paper some further discussion of what I would call the upper and lower limits; the lower limit being the problem of supplying hot water electrically to the working-class community, where every penny counts, and the upper limit being the semi-commercial or commercial installations, where the problems are not nearly so simple as in domestic work.

I agree with Mr. Humphreys that we should endeavour to educate everyone up to the use of a constant hot-water supply, but I submit that on the lower income levels such a course is entirely impracticable economically. It may be possible to provide a constant hot-water supply for sink use, but not for general household use. There are very many families to-day who are obtaining the supply of hot water that they need from simple wash boilers, electrically heated. I believe that there is a very big electrical market for that type of consumer.

Turning to the upper limit, namely wash-basins and sinks in restaurants and hotels, it is very difficult to make accurate estimates of the quantity of water required by such users. We can obtain reasonable estimates for group wash-basins for office use, but not for restaurant kitchens where the hot water is used for washing up. During the last year or two in my own district we have installed a number of heaters dealing with this type of problem, and in many cases we have put in water meters in order to obtain some figures on which to work. In one instance, that of a milk bar and café running a 24-hour service, we found that the consumption varied from 30 to 50 gallons per hour throughout the 24 hours of the day.

Storage alone is no solution to problems of this sort, as there is very little room in such premises for large storage vessels. It is therefore necessary to employ higher loadings. In the case to which I refer, the problem was met by a 100-gallon heater with 12-kW loading—6 kW at the top, to give quicker recovery, and 6 kW at the bottom. It was found in practice that during the 24 hours there was never less than 6 kW connected on that heater. On investigation we found that we could not have given the necessary service at a less loading than about 9 kW, so that the 12 kW actually installed was not excessive. An increase of storage would not have helped, because as the heater was in constant use there was no period of recuperation. The only improvement from a supply point of view would have been to install off-peak thermal-storage equipment, and to do that it would have been necessary, owing to the shape of the load curve in the district, to have had the heater disconnected from the mains for at least 10 hours a day, which would have meant providing a heater of 1 000 gallons capacity and about 20 kW loading, which it would have been impossible to get into the premises.

Other premises of this type, not open 24 hours a day, have been dealt with by similar types of heaters, and the load factors, even with these very high loadings, have varied from 47 % down to 18 %.

Mr. C. Hubert Smith: The author emphasizes in the first part of the paper the importance of the efficient application of electricity for water heating. This, of course, is where we can make good the disadvantage of electricity in the matter of the number of heat units which can be bought for a penny. Provided the installation is efficient, we can make a very good showing with electrical energy at its present price.

Turning to the question of hard and soft water, no general rule can be laid down as to where it is satisfactory to use copper or galvanized-steel containers. I do not agree that where the water is hard it is safe to use galvanized steel; there are certain classes of hard water which are corrosive, and great care should be exercised before specifying galvanized-steel construction for use with electric water heaters. One is, of course, always safe in using copper construction. Steel construction is satisfactory in certain conditions, but not necessarily when galvanized; sometimes a plain steel construction, treated, possibly, with some anti-corrosive composition, is more satisfactory.

If an electric water-heating installation is to be successful it must have a certain amount of storage—as much as the circumstances will warrant and the space will allow.

With regard to the tinning of copper water containers, some engineers say that tinning is unnecessary and others that it is absolutely necessary. It is a controversial point, because of the enormous variety of water supplies to be found up and down the country; and not only do the water supplies differ one from another but the composition of any particular water supply varies from time to time. What is certain is that any copper container that works on the displacement principle and therefore is not always full of water, should be tinned. The cistern-type heater should also most certainly be tinned, because it is often partly empty in the normal process of operation. Another method of dealing with the situation is to use a metal (e.g. monel metal) which does not require tinning at all. Although monel metal costs more than copper, it lends itself to manufacturing processes which enable savings to be made.

Heating elements have attained a wonderful degree of reliability; the present-day heating element, when working under reasonable conditions, will last for many years, and there is usually sufficient tolerance to allow of a certain amount of furring-up of the sleeves.

I do not agree with the author that scaling is largely a function of the watts loading per square inch of heating surface. There is only one way of ensuring that there shall be no furring-up in very hard water, and that is to use the indirect heating method with water as the heating medium; but unfortunately it is impracticable to apply indirect heating by water to the small domestic hot-water heater—there is not sufficient space to do so. As regards the question of loadings, the average user in England will not adapt his requirements to the performance of the water heater; he wants the water heater to respond to his own wishes. It was very soon found, therefore, that the loadings, as applied to the early heaters, had to be increased. The present standard loadings are very satisfactory for all-round purposes, but none the less they still have to be increased very substantially in many cases. For instance, some supply engineers insist on a loading of 2 kW for a 1½-gallon heater, because they find that a small heater loaded to 2 kW suits the needs of their particular community. Similarly, 100-gallon heaters are very often loaded up to 12–18 kW.

In regard to the definition of types of water heaters, I am glad that we have discarded many vague descriptions such as "semi-pressure," but why the pipe which runs from the top of a heater to a point above the ball-valve cistern should be called an "expansion pipe" I cannot understand. It is not really an expansion pipe at all, because the water does not expand up that pipe; it actually expands backwards through the cold-water system. What we know as the expansion pipe is really a vent pipe, and its primary function is to discharge the air which is liberated during the heating of the water.

A great deal of time has been spent over the design of 1½-gallon electric water heaters, and all kinds of ingenious devices have been thought out to overcome the difficulty due to those two contending factors, the expansion of water and the fact that the heater works on a displacement principle, with water control on the inlet. The present-day product is a very sound one, however, and gives satisfaction in hundreds of thousands of homes. The great point with 1½-gallon heaters, which have to work so hard, and particularly in difficult water conditions, is to keep them as simple as possible. If the water chamber contains a multitude of pipes and elements there will be many crevices in which "fur" can collect.

So far as immersion heaters and circulators are concerned, it must be borne in mind that it is impossible to make full use of the available storage capacity by using a circulator. With cylinders or tanks of ample size the top-entry arrangement is very good, but where the cylinders are small, as they are in some districts, it is very often better to put an automatically controlled immersion heater through the side of the cylinder, and so make use of the full storage capacity. It is possible to obtain more storage value with some arrangements of a top-entry heater than with others, but never so much as with a side-entry heater.

The circulator or immersion-heater installation should be worked in conjunction with a separate self-contained heater at the kitchen sink, because there is always a loss in the pipe-run from the cylinder to the draw-off tap in the kitchen. The sink heater may then be run at 160°–170° F. and the main system need not be run at more than 130°–140° F., because this is as high a temperature as will ever be required for the bath or wash-basin.

The author mentions a certain type of circulator which has part of the loading controlled by a switch and part by a thermostat. Where a thermostat is used in conjunction with a heater it is much better for it to control the whole of the load. If it is desired to control part of the load also by a switch, let the switch be subsidiary to the thermostat; it will then not matter if the switch is left on accidentally.

It is a good practice to fit a thermostat in conjunction with every immersion heater, either as an automatic controlling device or as a protective device to guard against accidental leaving-on. If the installation is sold as an automatically controlled installation, then the cylinder must be efficiently lagged; but if it is sold as a hand-switch-controlled installation, with possibly a thermostat to guard against accidental leaving-on, the lagging is not so important. I think that this is the line of demarcation in the argument between lagging and not lagging.

With regard to pipe losses, it is fortunate that contemporary with our efforts in the way of water-heating development there has been considerable development in the use of copper pipes, and copper pipework fits in very well with electric water heating; but it is necessary to bear in mind that it is undesirable to mix up copper pipes too freely with galvanized-iron tanks.

As regards the usefulness of thermal storage, for very big buildings it may be quite practicable, but, as to its application to private residences, the best way to come to a conclusion on this point is to try to find a suitable position for, say, a 200-gallon well-lagged storage tank or cylinder in one's own home!

In conclusion, I should like to emphasize that the welfare of the whole electrical industry is wrapped up in the advance of the electric water-heating idea. Every water heater which is sold means extra load, extra cables, and extra plant; it affects the whole industry.

Mr. R. W. Minter: The author omits to mention two types of water heater which should be dealt with if the paper is to cover the scope indicated by its title, namely the instantaneous heater and the electrode boiler.

So far as instantaneous heaters are concerned, the author disposes of them in one short paragraph. Whilst it is perfectly true that the thermal-storage heater is the best type of installation where it is the only electrical appliance, apart from electric light, that the consumer has, surely electrical engineers should look forward to the time when every house will be all-electric. There are many instances where the instantaneous type of heater is preferable to the thermal-storage type. The author implies on page 3 that a 4-kW geyser would be suitable for supplying a bath; a much greater loading would clearly be required to overcome the difficulty of cooling of the water. The instantaneous heater is cheap, far more reliable than the storage type, does not fur up, and avoids the usual storage losses.

With regard to scaling, surely this trouble is entirely due to the fact that the heating element of the present type of thermal-storage water heater is much too concentrated.

Under the heading "Larger Heaters," the author says that each hot bath requires a minimum of 10 gallons of water at heater temperature, and that a 20-gallon heater can be used to give two hot baths in quick succession. I contend that it is not possible to obtain two hot baths in quick succession from a 20-gallon heater loaded at 2 or 3 kW. The reason for this is that a considerable amount of cold water goes direct to the top of the tank; it certainly does in my own thermal-storage heater.

I do not agree with the suggestion, made on the same page of the paper, that the poorer people should have to have a type of thermal-storage heater which will provide a hot bath only at intervals of 2–3 hours, nor do I agree that such a system is comparable with the conventional fuel-fired system installed in small houses. The makers of the best fuel-fired systems would be very upset if it were suggested that their products would not give a hot bath every half hour.

I think that immersion heaters should be regarded merely as a stepping-stone, to be discarded at the earliest opportunity. The author's figures for the losses from them do not seem to agree with other published data. It is stated in the paper that the loss from a 20-gallon tank corresponds to a consumption of 2 kWh a day, but Mr. Bolton, in his book on water heating,* gives it as 16 kWh a week for the very best type of thermal-storage heater.

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* D. J. Bolton, P. C. Honey, and N. S. Richardson: "Electrical Water Heating, with special reference to the Domestic Storage Heater" (Chapman and Hall, 1935).

I cannot support the suggestion that poorer people should have a switch-operated unlagged tank. What is wanted is a thermostat and switch. If the consumer does not want a bath every day he can leave his switch off, and when he wants hot water he switches on but still has his protection against overheating.

I do not approve the practice of always using a central water storage system. The proper place for an electric water heater, since electricity is so wonderfully flexible, is where the water is wanted and nowhere else, i.e. at the sink and in the bathroom.

I mentioned electrode boilers because in Fig. 14 we are given the consumption of electricity for water heating in a large block of flats, and it seems to me that the electrode boiler might be better in a case of that kind than any form of thermal-storage system, with its tremendous losses.

Regarding the author's remark that the water-heating load of this country is supplied at the normal running rate of the two-part tariff, I would point out that a large number of municipalities supply it at a lower rate. I do not believe that the water-heating load is of sufficient importance to warrant a special rate; it is not the largest application of electricity to the home, as the following figures taken from my own installation will indicate. I make the definite statement that room heating is the most satisfactory load that the supply engineer can have in domestic premises. When I designed my own all-electric house I estimated that, for a full year, room heating would cost £13 15s. 0d., cooking £4 4s. 6d., lighting £1, water heating (not counting the losses) £2 2s. 6d., and washing machine (loading 6·25 kW) £1 16s. The bill for energy for the year was £24 4s. 1d. I had estimated my water-heating bill, exclusive of the washing machine, at £2 2s. 6d., and the actual bill was £2 12s. 8d. for the year. Assuming that my estimate of £1 16s. for the washing machine was approximately correct, the total annual water-heating consumption was £4 8s. 8d. Comparing this with my estimated cooking bill of £4 4s. 6d. it is seen that the water-heating load is also no better than the cooking load.

I am not in favour of the suggestion of carrier-current control of the consumer's load. The business of the supply undertaking is to give an adequate supply to meet the wishes of the consumer, not to think of ways and means of restricting the consumer's habits of living.

Mr. R. Grierson: I agree with Mr. Minter that the title of this paper is a little misleading; I had hoped that the author would deal with a few of the more practical points which arise.

On page 1 it is suggested that in soft-water districts the CO_2 content of the water is the cause of corrosion. I should be grateful if in his reply the author would indicate his authority for that statement.

He comments on the variation in the consumption of hot water in the smaller houses, but surely there is a very reasonable explanation. If the consumption of the 3- or 4-bedroom house of the £1 000–£1 500 class is averaged at 60 kWh per week, and the efficiency of the installation is assumed to be 90 %, the net heat consumption is the equivalent of 54 kWh or 183 600 B.Th.U. per week. Assuming the temperature of the water is raised from 50° F. to 140° F., then the consumption of hot water is 183 600/90 = 2 000 lb., or 200 gallons. One bath per week, calling for 16 gallons, represents 8 %, two baths represent 16 %, etc., of the average weekly consumption; washing machines are also another cause of the variation in consumption, as the usual capacity is approximately 9 gallons.

I must join issue with the author regarding the maximum temperature of the storage water, for I consider that high temperatures are only justified as a last resort, to enable one to provide an effectual service of hot water from an existing tank or cylinder of inadequate capacity. With the price of energy at ½d. per kWh we must strive for the last ounce of efficiency that it is possible to obtain from an installation. If the ambient air temperature is 60° F. and the water temperature is 140° F., then the temperature-difference between water and air is 80 deg. F.; and if this temperature-difference is raised to (180 − 60) or 120 deg. F. the increase is 50 %, and this increase must invariably result in an increase in the standing losses. Risk of scalding (i.e. turning on the tap and not expecting such exceedingly hot water), damage to the porcelain and enamel of baths and basins, and the additional losses in dead-legs, all form arguments against high storage temperatures.

The author's reference on page 3 to test and working pressures is a little ambiguous, and it should be made clear that working pressures should in no case exceed 50 % of the test pressure.

I have recently encountered a case of corrosion of an untinned copper cylinder, the pitting and eventual perforation occurring on vertical lines on the inner side of the cylinder. Although the cause is obscure and the failure is an isolated one, the discoloured drip markings commence at the joint between the dome and the barrel, and it seems probable that either the solder or the remains of an active flux may provide the explanation.

Micro-gap thermostats of certain makes have been made to function satisfactorily on 230-volt d.c. circuits where the current does not exceed 10 amperes, by the addition of a condenser of suitable capacitance connected directly across the contacts of the thermostat.

Granulated cork is undoubtedly an effective heat-insulating material, but in practice it is found to "pack" to a considerable extent during the first few weeks, probably owing to the alternate expansion and contraction of the storage vessel. This "packing" involves a second visit to the installation to "top-up" with additional cork, and this adds to the cost of conversion. A non-packing type of insulation, such as red cedar-wood fibre, has been found to eliminate the necessity for this second visit.

It is interesting to note that for a payment of approximately £7 10s. the consumer may either have a 1½-gallon unit type of water heater installed, or, alternatively, he may have an existing 30-gallon tank installation converted to electric operation by the addition of an immersion heater, thermostat, heat insulating material, and wiring.

Although it may reduce the initial cost of an installation, it seems to be unwise to locate the thermostat immediately above the immersion heater when this is in the horizontal position, i.e. in the convection stream of hot water rising from the immersion heater; because if this is done the thermostat tends to switch off prematurely, and consequently the number of thermostat operations per year must be substantially increased, and the life of the thermostat contacts be reduced. This practice will also tend to increase the recovery period by decreasing the number of B.Th.U. transmitted per hour to the water.

The majority of complaints of inadequate hot-water service that I have investigated have proved to be due to the installation of vertical heaters combined with thermostats or (so-called) circulators, fitted down through the upper dome of the cylinder. In each case the consumer has been more than satisfied when the cylinder has been re-fitted with a heater and thermostat fixed at low level, and the improved performance has been verified by records obtained from pipe thermographs, water meters, etc. The complaint has been the same in each case—" a bucket of hot water, and then it runs cold." The reason for the complaint is obvious: the cylinder being filled with cold water, the thermostat closes circuit, the heater functions, and eventually the thermostat opens circuit when it is immersed in hot water. Hot water is drawn off and is replaced by cold water, which lies at the bottom of the cylinder, in sight of, but out of contact with, the thermostat. If the hot water is drawn off in small quantities, the cold water rises slowly, and the cylinder may be more than half-full of cold water when the consumer decides that a bath is required. It may be argued that, commencing from the top of the cylinder, the water is very hot, hot, not-so-hot, warm, lukewarm, cool, cooler, and cold at the bottom; and that when one of these strata immerses the thermostat the contacts will close and the heater will function. If the cylinder had ample capacity the result might be satisfactory, but when the cold-water capacity is only 20–25 gallons every inch of vertical height is required for the storage of hot water at a temperature of 140° F. in order to ensure satisfactory results. Vertical heaters also induce an excessive deposit of scale (due to the excessive temperature at the top of the cylinder) and also reduce efficiency, owing to the necessity for eliminating the heat insulation at the hottest part of the cylinder, in order to accommodate the heater. Efficiency is still further reduced by the addition of exposed hot metal represented by the circulator head. A typical " circulator " head is of 3¾ in. diameter by 4 in. high, and contains approximately 58 sq. in. of exposed metal at the maximum temperature, as compared with the area of the dome of a 16-in. diameter cylinder of 201 sq. in.; that is, the fitting of a vertical heater through the dome of a 16-in. diameter cylinder increases the area of the dome by 29 % at the hottest (and abnormally hot) point in the cylinder.

The new clamp-on type of thermostat appears to solve the temperature-control problem for us, and I hope that some of our manufacturing friends will devote their inventive faculties to the production of angle-type bosses which will enable us readily to insert a magnesia-oxide-filled 2-kW 10-in. long heater into the majority (if not all) of the indirect type of cylinders, at a point low down in the vertical wall or barrel of the cylinder.

I am glad to note that the author refers to the airing-cupboard problem. The removable pad is not the final solution of the problem, for when the consumer complains about his quarterly account he is invariably positive that either the pad has never been removed or that it has only been off for an hour or two at most, whereas the meter reading provides reliable proof that it must have been off for days, assuming that the consumption of hot water was normal.

The statement is made in the paper that hot water will not circulate downwards, and this should be qualified. One of the most interesting complaints that I have investigated recently refers to a bungalow installation, where the cylinder was fixed 12 in. above floor level. Although the boiler flow pipe rises 11 in., and the boiler return pipe rises 1 in., between the boiler and the cylinder, in a run of approximately 10 ft. of ¾-in. copper pipe, reversal of circulation through the boiler was definitely proved by disconnecting the pipes at the boiler. With the pipes connected, no fire in the boiler, and the immersion heater in use, the consumption averaged 25 kWh per day and 175 kWh per week, whereas with the pipes disconnected the consumption averaged only 12·5 kWh per day. In this connection, Mr. T. F. Holman* makes the following interesting statement: " Extent of circuit is immaterial, and it would be quite simple to warm the Bridge Gate office at the south end of the Tower Bridge from a boiler fixed in the North Gate office, carrying both flow and return mains via the high-level footways." I have definite cases on record in which the immersion heater fixed in the indirect cylinder on the first floor has heated the secondary water, which, in turn, has heated the inner concentric cylinder, and again, in turn, has heated the primary water. The primary water has then commenced circulating in the vertical pipe to the loft, crossed the loft, descended to the ground floor, and returned to the cylinder, on the first floor, heating the boiler en route. It is not an uncommon practice in America to fix the storage cylinder on the floor *below* the boiler, care being taken to make the length of the rising flow main to the roof at least twice the vertical distance between the storage cylinder and the boiler situated above it.

A point with which the author does not deal, but which is of very considerable practical importance, is the general experience of hot-water supply engineers who have encountered installations incorporating galvanized storage cylinders and copper pipes or vice versa, and the possibility of electrolytic action between the two electrically dissimilar metals. Another interesting point is their experience with the base-exchange type of water-softening plant, when installed in conjunction with galvanized pipe installations, with or without the use of sodium-silicate injectors, or of special provision for mixing raw and softened water in order to arrest the process of corrosion of the immersed metals, i.e. in order to maintain a protective coating of scale.

On the question of high loading versus low loading of storage vessels, the former do their job and switch off, whereas the latter persist for some hours and inevitably contribute their quota of the load to the 7 a.m.–10 a.m. peak. With the housing-estate type of installation where the consumer rises between 6 a.m. and 6.30 a.m.

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* " Essentials in Hot-Water Circulation," *Journal of the Institution of Heating and Ventilating Engineers*, 1938, vol. 6, p. 292.

and is at work at 8 a.m., heavily-loaded heaters are probably off supply by 8 a.m. or 8.15 a.m., whereas low-loaded heaters continue on the mains for a considerably longer period.

Mr. G. O. McLean: When dealing with the lagging of existing tanks and cylinders the author mentions that forms of lagging made up on site are commonly used, but he does not tell us much about them. I should like to say that a fair amount of *in situ* lagging is done with the red cedar-wood fibre which was mentioned by Mr. Grierson. Last summer we tested an installation consisting of a 30-gallon copper cylinder with a 2-kW immersion heater and thermostat situated in a cupboard formed by three brick walls and a wooden door, with a minimum of $2\frac{1}{2}$-in. clearance between the sides and the cylinder. The space was filled with small cork granules, the total weight of cork being 36 lb. With the thermostat set at 175° F. and an ambient air temperature of 70° F.—this was in June—the average daily radiation loss over a week's test was 1·5 kWh. The cork was then taken out and replaced by 30 lb. of red fibre, and a further week's readings were taken without drawing off any water; the average daily loss was found to be 2 units. Laboratory tests show, however, that the thermal conductivity of the red fibre and of such other forms as flax and jute is actually as low as that of cork granules. We then tried teazling the fibre out. We filled the space with 10 lb. of teazled fibre, and with that there was a loss of 2·8 units per day. Nevertheless, the fibre had some advantages over cork. For instance, there was much less dust and there was no odour, whereas with cork there is a considerable smell on first heating-up, and sometimes this lasts for a fortnight. The most important advantage, however, is that the fibre stays in position. It was possible to remove the matchboard front of this improvised cupboard and alter the thermostat settings without disturbing the fibre, whereas with the cork we had to build a little box round the thermostat in order to be able to get at it, and if the matchboard front was moved all the cork came out. With a cork-lagged installation the floor boards have to be covered, especially round the pipes, as otherwise the small granules run down.

Referring to an electrically heated towel-rail, the author says: " This method of drying wet towels is much more economical than omitting some of the insulation from an electrically heated tank." Has he not omitted to take into consideration the capital cost of the electrically heated towel-rail and the wiring cost? I also think that he has made a mistake about the actual running cost. If the top of the tank is left uninsulated there will be only 1 to 2 sq. ft. of metal exposed, which at 160–180° F. will dissipate only about 100–200 B.Th.U. per hour, or 70 watts at the worst, compared with 100 watts loading for a towel-rail. Furthermore, the author's immersion-heater tank and separate towel-rail together have a worse load-factor than the single-tank installation, and therefore from the supply engineer's point of view the single installation is to be preferred.

Mr. M. J. Gartside (*communicated*): A very valuable feature of this paper is the prominence given to the temperature gradient which exists between the top and the bottom of the usual design of storage water heater, or of a tank heated by a circulator, and the consequent result that the temperature of water drawn from the heater may differ considerably from the temperature setting at the thermostat. Mr. Humphreys mentioned that this difficulty has been overcome in the past by using thermostats specially set to suit the characteristics of the water heaters to which they are fitted; but this is not a very satisfactory expedient, as the following considerations will show. The temperature gradient existing in a water heater is always greater when the water heater is first heated up from cold, while after it has been heated up for some time with no water being drawn off, the temperature gradient is quite small. Now if a short-stemmed thermostat is set low enough to prevent boiling during the first heating-up of the water, that same setting will result in a comparatively low temperature being obtained after the water heater has been standing by for some time.

This point is of particular importance in connection with the modern design of $1\frac{1}{2}$-gallon tank in which an element almost as high as the tank is employed of fairly high loading. Modern practice is to use a thermostat as long as the element, and where the elements are mounted vertically this is usually an advantage, bearing in mind that thermostats more than 18 in. or 24 in. long are hardly practicable.

This consideration of temperature gradient and its effect on the relation between outlet-water temperature and thermostat setting is one of considerable importance, as lack of realization of the apparently anomalous results which can be obtained causes unjustifiable complaints regarding thermostat calibration. The value of the paper would have been increased by the inclusion of curves, similar to those in Figs. 6A and 6B, for the modern designs of storage water heaters.

The question of the use of the micro-gap type of thermostat with condensers for direct-current work has been mentioned in the discussion. Success is being obtained with micro-gap switches and condensers used in this way, but precautions must be taken: firstly, to ensure that the condenser is one suitable to withstand the fairly high ambient temperature found under the apparatus plate of the water heater; and secondly, that the connections between the condenser and the thermostat are made as short and as thick as possible in order to reduce inductance and resistance, and are made in such a way that the condenser is never likely to become disconnected. Provided these points are taken care of, then the combination of thermostat and condenser seems to be a more satisfactory arrangement for direct-current use than the mercury-tube type of instrument.

With reference to the micro-gap or short-break magnetic type of thermostat, a valuable function of the magnet is that it provides the necessary snap action of the switch in an entirely frictionless manner.

Mr. R. B. Rowson (*communicated*): The proportion of space allocated in this paper to engineering details and the economics of water heating respectively affords a striking commentary on the lack of balance from which the electric supply industry tends to suffer. In spite of the special facilities the author must have, he is not able to put forward any definite figures regarding the characteristics of the water-heating load under English conditions, but is compelled to refer to American statistics. One would have thought that before trying, as they have done, to encourage this load by a national advertising campaign the British supply industry would have carried out fairly extensive experiments to ascertain its economic effect.

In general, English engineers seem to be of the opinion that the load is almost, or entirely, off peak, whilst American engineers know from their investigations that this may not be so unless the hours of use and the relation between capacity and loading are controlled. The necessity for some control was emphasized in a recent review of water-heating tariffs* which showed that the present trend in the U.S.A. was for special rates to be offered for night use only, and for the watts per gallon to be reduced to 20–25 for night heating and to 30–40 for daytime boosting. It has also been shown† that with the heater continuously connected to the supply and thermostatically controlled the demand at 9 a.m. was very substantial. This latter fact appears to be reasonable in view of the shape of the "draw-off" schedules given in the National Electric Light Association report. If the above-mentioned result is compared with the load curves of Hastings and Wimbledon‡ it will be seen that there is a fair chance that the thermostatically controlled unrestricted water heater increases the system peak and as a consequence the tariff offered should include some kilowatt component.

In view of the above remarks it is difficult to appreciate how the loadings given in Table 3 of the paper can be satisfactory from the point of view of the supply undertakings, except on the assumption that hot water is obtained by other means in the winter. It is interesting to note from page 16 that some water undertakings, faced with similar difficulties, take a realistic attitude.

The author mentions that the load might be controlled by one of the remote-control systems. Apart from capital charges, the technique of operating such systems for off-peak control is difficult if the load factor of the undertaking is fairly good to start with. The precise moment when the heaters should be cut off so that the demand of the undertaking is not increased, and yet at the same time the users are not inconvenienced, is extremely difficult to determine. A study of one particular system indicated that the installation of remote-control gear would not be of material assistance unless the consumers also used reasonably large tanks.

The possibility of the demand due to the water-heating load overshadowing the demands of other loads must not be overlooked. This condition has occurred in New Zealand§ and appears to have put the supply authorities in a very difficult position. An idea of the magnitude of the potential water-heating demand may be obtained from Table 2. If heating could be restricted to 8 hours per day and could take place at a uniform rate, the demand would be about 6 500 000 kW. This figure, being based on averages, is likely to be exceeded, especially as the size of heater installed will have to be large enough to meet demands for hot water well above the daily averages given. It seems, therefore, safe to say that the potential demand is greater than the total present maximum demand of the country for all purposes.

As an alternative the load could, with suitable restrictions on watts per gallon, be supplied at, say, a 50 % to 60 % load factor with a maximum demand of, say, 4 000 000 kW. As, however, the price per unit would have to be, say, $\frac{1}{3}$d., it seems doubtful whether this would be economically possible and whether it would be advisable from the national point of view to spend, say, £200 000 000 in putting down plant and mains to supply a service which can be, and is being, met by alternative commodities.

In connection with Table 2, it is difficult, even allowing for the differences in income, to see how the larger and poorer families are to manage with 7 gallons of hot water per day. The proportion of families having incomes from £250 to £500 is larger than I had been given to expect from other estimates, and perhaps the author would mention the source of his figures.

Mr. E. O. Taylor (*communicated*): The author has shown that electric water heating in domestic premises is technically possible in the majority of cases, but he has been less successful in justifying its use on economic grounds. This may be illustrated from my own experience in an 8-room house occupied by 3 adults and 1 child which is supplied throughout the year with ample hot water by a fuel-fired boiler at an average cost of 5d. per day (taken over 3 years). Using the author's figures given in Tables 1 and 4, and assuming 2 baths per day and 10 fillings of the wash-hand basin, the consumption of electrical energy would be 13·72 kWh per day. To compete with the fuel-fired boiler, therefore, the cost of electricity would have to be not more than 0·36d. per kWh. Actually the above estimates of consumption and those of Table 4 would involve considerable care and economy in the use of hot water, so that for most average households an even lower cost per kWh would be necessary. Furthermore, in addition to providing hot water, the fuel-fired boiler provides heat for one room and also enables perishable refuse to be burnt—an important feature when dustbins are only cleared once per week.

An ample supply of hot water is probably the most effective of all the possible labour-saving devices which can be installed in a house, but it would appear from the above figures, which seem to be typical for a house in which the residents are in continuous occupation, that electric water heating cannot be economic unless the cost of energy is as low as about 0·3d. per kWh.

[The author's reply to this discussion will be found on page 50.]

* *Electrical World*, 1937, vol. 107, p. 33.
† *Ibid.*, 1932, vol. 100, p. 722.
‡ *Electrical Review*, 1939, vol. 124, p. 20; and *Electrical Times*, 1939, vol. 94, p. 29.
§ *Electrician*, 1937, vol. 121, p. 781.

WESTERN CENTRE, AT GLOUCESTER, 12TH DECEMBER, 1938

Mr. C. W. D. Newman: Makers of electric water heaters so design them that, with a minimum of trouble, apparatus plates may be withdrawn for the purpose of inspecting the deposit of scale which has formed upon them. Unless electric water heaters are to be discarded in districts where the only available water supply is heavily charged with scale-forming ingredients, however, some simple and thoroughly effective means of causing scale-shedding from the apparatus must be devised.

Experience with evaporators in the engine room at sea leads me to believe that this is practicable. No scale-shedding at all from scaled-up evaporator tubes will result from blowing-down an evaporator and then quickly refilling it with cold water. The reason is not far to seek. The scale, formed on the copper tubes as tightly fitting concentric tubes, was deposited when the copper was at its normal working temperature. Scale is a remarkably bad conductor of heat; but has quite appreciable mechanical strength in compression. Consequently, the copper tubes, within their protective coating of scale, do not cool and contract very much; and the scale tubes do not collapse and break up into fragments. If, however, after an evaporator has been blown-down, and while it is still empty, the heating steam be turned on liberally through the copper heating tubes, they will rapidly expand to dimensions in considerable excess of those obtaining when they received their coating of scale. Then, since scale has a low coefficient of expansion relative to that of copper, and is moreover fairly weak in tension, it is vigorously, inexpensively, and very effectually shed. In this way the efficiency of an evaporator can be maintained indefinitely, but within a limit imposed by the space taken up by accumulation of shed scale.

Analogous treatment would appear to be feasible in the case of electric water heaters, provided only that the elements are made robust enough to stand up to the drastic de-scaling technique I have described.

It should be possible to arrange for the necessary apparatus to be available for periodic operation by the service department, with the heaters in situ in consumers' premises, and yet as inaccessible to the householder as, say, coins in a slot-meter.

Mr. C. G. Agg: Is it not a fact that a water heater with a glass container is on the market? If so, will this do away with some of the disadvantages of existing containers, such as (i) absorption of copper into water and (ii) corrosion on iron containers?

I have noticed that if granulated cork is used for lagging and this for some reason gets overheated it gives off an oily substance. This forms on the porcelain container and gives the appearance of rust, due to its "rust" colour. This is worth noting, as it may mislead an inspector into thinking that a leak exists in the inner container.

Mr. J. F. Edgell: Whilst the author is probably correct in that most of the salts are not precipitated until a temperature of 180° F. is reached, I believe that quite a lot of precipitation occurs at a much lower temperature; and, further, I submit that the temperature at which liberation of the CO_2 gas occurs is governed to a very large degree by the turbulence of the liquid, and in particular by the stresses within the liquid, due to the diverging of the convection currents. We have to remember that it is the liberation of the CO_2 gas that is the root cause of scale formation.

In Gloucester we have two distinct types of scale. The more common varies in colour from pure white to dark brown, depending on the quantity of ferric oxide and alumina present, but chiefly on the rate of deposit of the calcium carbonate. The white deposit is almost entirely calcium carbonate, with only about 1·4 % calcium sulphate, and its spongy structure denotes rapid deposit. The slower the rate of deposit of calcium carbonate, the more crystalline and hard is the scale formed. This spongy deposit does not shed in service, nor does the harder variety shed readily.

The other form of scale sheds very readily, and accumulates in the lower part of the heater, leaving the tinned copper surfaces from which it is shed comparatively clean. This formation is of the nature of aragonite mixed with calcite, both of which tend to agglomerate to hard compact masses.

The author considers it strange that individual hot-water requirements differ to such an extent; whereas in my opinion it would be strange if they did not. The human being possesses an individuality, and, moreover, is capable of exercising it; hence one cannot average his requirements unless some other factor has a predominating influence. A coal miner, a chimney sweep, or a foundry hand, would conceivably have similar hot-water requirements, but other people are more free to exercise their likes and dislikes. Incidentally, as a general rule, elderly people have smaller hot-water requirements than the less mature. Income, I find, has practically no influence, assuming establishments of the same size.

The figures of percentage saturation in other countries (page 1) reflect economic and tariff conditions in those countries. Water heating has a high elasticity compared with lighting, as it is still regarded as one of the services in which electricity has little advantage over competitive methods.

A pressure test of 50 lb. per sq. in. for water containers (page 3) would not satisfy our requirements in Gloucester, as the normal mains pressure in many districts is 65 lb. per sq. in. We ask for a test of 120 lb. per sq. in., and this almost necessitates the welded construction mentioned by the author.

I do not agree that tinning is unnecessary, as I have too often seen the result of the action of tap water on unprotected copper. The corrosive effect of carbonic acid (H_2CO_3) is well known in cistern-type heaters in particular.

On page 3 the author appears to have confused the necessity of keeping the element wire within its temperature limits with the mechanics of scale formation. The amount of scale deposit which forms in a water heater designed for hard-water service depends upon how bad the design is. Scale is thrown out where CO_2 is evolved, and the primary cause of CO_2 evolution at temperatures near the critical is turbulence, which is created by convection currents. Long heater tubes are a source of convection currents, and hence of turbulence, leading to scale formation. The scale thrown out is at a maximum where the convection currents diverge, because here are the maximum turbulence and the maximum stresses in the liquid: hence the characteristic shape of the scale deposit, on the outlet and thermostat tubes as well as on the heater tubes.

Heavy scale deposits form on the outlet tube if the design is such that turbulence is pronounced when water is drawn off. An enlarged outlet reduces turbulence, and hence scale deposit at the mouth of the tube.

Scale will of course form on the heated surface with which the water is in contact, but it becomes a problem only when we so dispose the heating surfaces and tubes that scale formation is encouraged on those surfaces. Scale deposit may also be encouraged owing to turbulence caused by a poorly designed inlet baffle.

In the case of four heater interiors that have been in service in " test positions," each position known to yield similar results when similar interiors are employed, No. 1 interior, having a loading of 5 watts per sq. in., failed early and carries a very heavy scale deposit. No. 2, with 10 watts per sq. in., has a scale deposit of some $\frac{3}{4}$ in. radial thickness on the outlet tube as well as the heater tubes, the deposit being slightly greater on the outlet tube. No. 3, with 12·5 watts per sq. in., has a deposit of some $\frac{1}{4}$ in. radial thickness. No. 4, with 14·5 watts per sq. in., has a deposit of less than $\frac{1}{8}$ in. radial thickness. I would suggest that these heaters furnish evidence that watts density has little bearing on scale formation in a well-designed heater. No. 1 failed owing to complete choking-up of the outlet tube, due, I submit, to the hemispherical anti-drip siphon device producing much turbulence at this point.

The heat-loss figures given in the paper are, in my opinion, low. I would draw the attention of the author to the results of tests reported recently in the *Electrician*.* Three heaters, when tested over a considerable period, gave daily radiation losses of 0·88, 0·87, 0·86 kWh respectively. Does the author dispute these figures?

Standardization of pipe sizes and wall-fixing centres is not enough. $1\frac{1}{2}$-gallon apparatus plates purchased in 1935 from one of the two manufacturers mentioned by the author are not interchangeable with those purchased in 1936, nor are either of these interchangeable with those purchased in 1937, without plumbing alterations.

Turning to the special anti-scaling heaters mentioned on page 6, the only one that is reasonably satisfactory is that shown in Fig. 5A(*a*), and its success is due to the outlet being out of the path of the convection currents. I can find no excuse for the unit shown in Fig. 5B ever having been designed as a hard-water heater. It is a fundamental error to have moving parts—springs and rubber plungers—inside a water heater, where they are all subject to scale deposit.

Simplicity is an essential feature of the design of a water heater if it has to operate in hard water. Low wattage is essential only when the design is such that heavy scale deposits occur on the heated surface. Heavy scale deposits can be avoided by reducing the length of the heater tubes and displacing them from the centre line; in short, by reducing the convection currents. Low wattage per square inch is helpful only in so far as the velocity of convection currents is lower than with high wattage.

Mr. R. W. J. Cockram: For families where the income is £250 per annum or less a thermal-storage heater for supplying hot water to the bathroom is often uneconomical since it will in all probability only be used on one or two evenings a week, and the rest of the time, if left connected to the electricity supply, it will be absorbing energy owing to its inherent losses. The immersion-type heater has an improved utility value when fitted vertically in the household cylinder, but has the disadvantages of expansion and draw-off pipe losses, while still quicker top heating and hence further increased utility would be obtainable if the ratio diameter/height could be reduced. This increased utility is met by the unlagged self-contained heater of 15–20 gallons capacity fitted with elements and draught tubes and loaded to 3 or 4 kW. This heater will provide a small quantity of hot water in a very few minutes, and if required will heat the whole contents of the container in a short while. Being self-contained, it has no pipe losses. The heater may be of the displacement or non-pressure type for providing service to two adjacent points by means of a swivel outlet, or, where water supply authorities permit it, may be fitted with a ball valve connected to the water mains and service obtained to a number of distant points. In the latter case, in order to counteract the fall in level of the water due to the draw-off rate being in excess of the feed rate of the ball valve, a special form of floating outlet is incorporated.

For supplying the kitchen, however, I agree that the small thermal-storage heater is very suitable, since hot water is in fairly constant demand in the kitchen throughout the day and the cost of running overnight is offset by the fact that hot water is available on demand the next morning.

I therefore suggest that for families where the annual income is £250 or less a small thermal-storage heater for kitchen use, and a non-pressure type of accentuated quick-top heating and self-contained heater for the bathroom, is the most economical form of electric water heating available.

I see that fire-back boilers are still included in pipe diagrams. Cannot the all-electric house be proved to be an economic proposition, or is it desired that electricity supply should only be developed along certain restricted lines, owing to the mains and feeders being too small to carry the increased demand which would be experienced if all properties were run on all-electric lines? If the latter is the case, then it appears that the use of electricity in this country is not going to progress with the rapidity which is within its possibilities.

Mr. J. C. Sanders: On page 3 the author mentions that " the amount of scale deposited therefore depends upon the density of heat transmission through the surface of the heating elements, and it is found that if this can be reduced to 10 watts per sq. in., scaling is slight. Another method of preventing deleterious scaling, which is probably preferable, is to make the heating element so long and so thin and of such a shape that its expansion and contraction during heating and cooling is sufficient to fracture and throw off the deposit of scale, and thus prevent it from adhering in any dangerous thickness." Whether elements can be made to descale themselves by increasing the watts density and reducing the diameter is a very debatable point, but I submit that if a thermal-storage heater is tested to destruction in a hard-water area the heating elements will not be found to be the limiting feature. The scale problem cannot be solved by designing a thermal-storage heater with long elements having a high watts density in the hope that these elements will descale themselves, as excess scaling will take place at other portions of the heater. Let us consider for a moment the question of the formation of scale from its chemical aspect. Water which is said to be temporarily hard contains in solution, in the main, salts of calcium and magnesium, in the form of bicarbonates. These bicarbonates, on being heated, give off CO_2 and deposit calcium and magnesium carbonates. Again, the carbon-dioxide gas which is given off combines with the calcium hydrate in solution to form calcium carbonate. These two reactions are represented by the two equations:—

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* *Electrician*, 1938, vol. 121, p. 622.

$$\begin{aligned} Ca(HCO_3)_2 &= CaCO_3 + CO_2 + H_2O. \\ CA(OH)_2 + CO_2 &= CaCO_3 + H_2O \end{aligned}$$

These equations may then be combined into one which illustrates both reactions, namely

$$Ca(HCO_3)_2 + Ca(OH)_2 = 2CaCO_3 + 2H_2O$$

It is these crystals of calcium carbonate deposited on the various internal parts of the heater which are known as scale.

Let us now apply this equation to a water heater operating in hard water. When the heating elements become hot, small bubbles of carbon dioxide form around their sheaths, and rise slowly to the surface, combining with the calcium hydrate as they rise to form crystals of calcium carbonate. These crystals, as they form, tend to settle on the nearest metallic surface available. If the heating elements are of sufficient length, the bubbles of carbon dioxide given off by the lower portion of the elements tend to form deposits of calcium carbonate on the upper portion of the elements. It has been proved by experiment, however, that if the length of the elements is kept within a certain maximum value, this tendency is almost entirely overcome. This indicates that the first essential in the design of a water heater for hard-water areas is short elements.

Again, experiments show that the rate of liberation of carbon dioxide is in direct proportion to the element temperature, i.e. to the watts density, and as the amount of scale formed is in proportion to the amount of carbon-dioxide liberated it follows that the second essential is low watts density. It has also been established that a high watts density gives rise to the formation of much larger crystals than a low watts density, the reason for this being that in the latter case the crystals are produced more slowly, and hence are more completely formed.

From the above our conclusions are, therefore, that in a water heater designed to operate in hard-water areas the following points are essential: (*a*) Heating elements must be designed with the lowest possible watts density, in order that the amount of scale formed shall be a minimum, and also to ensure that what scale is formed shall consist of small crystals. (*b*) The heating elements should not exceed a certain maximum vertical height, such that excess deposit of scale on the upper end of the elements does not occur. (*c*) It will be observed that (*a*) and (*b*) are contradictory, in so far as reduced element length naturally results in increased watts density. To overcome this, rather than increase the diameter of the element, which would tend to result in higher element temperatures, the number of heating elements should be increased.

From the point of view of operating efficiency, the following factors must be borne in mind.

(1) Decreased element length, together with low element temperatures, will result in a better internal temperature-gradient, which will again result in the water at the bottom of the container being at approximately the same temperature as that at the surface. This means that an increased number of B.Th.U. can be stored in the same heater with the same maximum temperature. This point is of paramount importance in the design of small water heaters, as it is easily possible to obtain as much hot water from one manufacturer's 1½-gallon heater as from the next one's 3-gallon size.

(2) A design of heater with no appreciable temperature variation having been achieved, it now follows that one universal thermostat setting can be used for all sizes of thermal-storage heaters, and in addition the dial setting of the thermostat will agree with the draw-off temperature. This will obviate the necessity for thermostat calibration charts, which I believe are being fitted in certain cases, giving the relation between the thermostat setting and the temperature of the water which the consumer may expect from the outlet.

I therefore suggest that a water heater which has been designed so as to give the best possible results in hard water will also give the best results from a heat-storage point of view.

Mr. G. G. Burton: On page 6 it is stated that the head of the cistern-type heater is limited to the vertical distance from the water level in the cistern to the outlet. This is not the case with the majority of cistern-type heaters, which are of the variable-volume constant-temperature type, so that the minimum head is equal to the height of the outlet above the highest outlet valve. In a heater of this type the rate of flow from the cistern to the heater is restricted to the rate at which the elements heat the water, so that the whole content of the heater is withdrawn at constant temperature.

The author makes no mention of the ejector type of anti-drip device. This is a great advance on the siphon type, which has the following disadvantages: (1) A minimum volume of 4 % of the capacity (the amount allowed for expansion) can be withdrawn from the heater. This is a disadvantage when filling small vessels from the displacement-type heater, and in addition causes wastage of hot water. (2) The top of the outlet pipe has a great tendency to fur-up in hard water, so that no device should be fitted which will increase this tendency, either by restricting the water flow or by providing a surface on which the fur can rest. (3) A siphonic trap is unsuitable for use at low pressure, as gushing will occur under these conditions. This is because there is a minimum rate of flow from an outlet fitted with a siphonic trap, controlled by the difference in height between the free level of the heater and the outlet. (4) With a siphonic trap there is a time-lag before the water ceases to flow after the inlet valve has been closed.

The ejector type of anti-drip device utilizes the pressure of the incoming water stream, which is passed through a jet and arranged to empty a chamber enclosed in the heater during the period that water is flowing through the heater. When water ceases to flow, this chamber refills and thereby allows space for expansion.

Fig. 6B shows the heating curves obtained with two types of circulator, one having its elements wound over the full length, and the other having its elements wound in the bottom portion only. In the former case, the thermostat cuts off when the temperature of the water at the top of the tank is 208° F., and the temperature of the water 18 in. down the tank is approximately 160° F. It is stated in the paper that the thermostat is 18 in. long and that it is set at 150° F.; to what part of a tank does the temperature setting of the thermostat refer? In certain cases thermostats are calibrated to suit the top temperature of the tank, and in other cases they are calibrated to suit the mean temperature along the length of free rod, but neither of these methods of calibration seems to have been adopted in this case. Fig. 6B shows that the thermostat cut-off of the top temperature was 170° F., and the temperature 18 in. down was approximately 160° F. It is possible that the apparently high thermostat cut-off in the former case is due to a phenomenon known as first-cycle peak, which is associated with long elements.

The author does not mention the efficiency of water heaters as thermal-storage heaters; it is useful when comparing heaters to define an expression for storage efficiency. Storage efficiency may be defined as the ratio of the units that are stored in the water in a given size of water heater, to the total number of units that can be stored in that water heater at a given temperature.

Mr. F. W. Bell: Referring to the curves shown in Fig. 1, what is the main reason for the rapid increase in the number of water heaters installed in Great Britain since 1936? Is it (1) hire-purchase or hire schemes, (2) offering of special tariffs, or (3) improved designs?

When water heaters are to be sold in an area where there is a restricted-hour tariff (off from 2.0 p.m. to 6.0 p.m.): (*a*) Would the author recommend the fitting of 3-gallon capacity heaters where 1½-gallon would normally suffice? (*b*) If so, could the element loading in such heaters be standardized at, say, 750 watts?

Mr. Bernard Carlton Robinson: I want to make a plea for an extension to that section of the paper which deals with installation practice. I suggest that a booklet might be prepared containing diagrams showing the best practice and the pitfalls to be avoided. Such a booklet should have the widest possible circulation.

In my own experience I have met with the arrangement shown as "C" in Fig. 10, and I agree that the alteration can easily be overlooked. In Cotswold houses one frequently finds a circulating "loop" to an isolated bathroom, and this can be a source of unsatisfactory operation.

Where a square storage tank is employed it is sometimes found that the outlet pipe is taken not from the top but from a point about 2 in. down one side. This is very bad practice where an immersion heater is to be installed, as a considerable amount of hot water will have to be produced before any is drawn. The units expended on heating this water are, of course, entirely lost.

Mr. W. Roberts: I am interested to note how closely the figures given in Table 8 agree with my own experience. In an 8-room house I have had installed a 30-gallon tank with a 3-kW thermostatically controlled heater. The household comprises five people, and we feed a wash-basin and bath, a kitchen sink, an outside wash-house, and three bedroom wash-basins. Accurate records show that throughout the summer and winter period over a year, the maximum and minimum weekly consumption figures were 109 and 64 units.

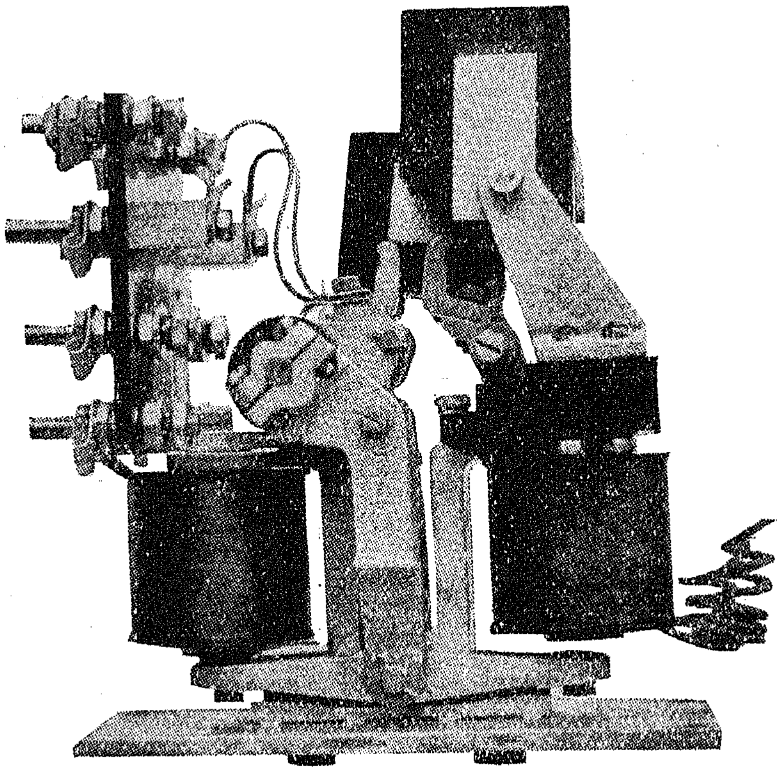

Fig. A

Momentary excitation of the right-hand coil closes the contacts and leaves them closed. Momentary excitation of the left-hand coil opens the contacts and leaves them open.

The avoidance of peaks might be dealt with by a double-circuit contactor (see Fig. A) which would leave the hot-water supply connected until the cooker was switched on. A change-over switch, admittedly, does the same duty, but leaves the consumers with the knowledge that they are not getting water-heating at certain periods, which might be regarded as an inconvenience.

Although this is a point which does not affect the electrical circuit, the general efficiency of an installation would be improved by lagging the feed pipes between the kitchen boiler and the cylinder. In some installations a run of 50 ft. between the boiler and the tank is encountered, and this undoubtedly is a source of great loss.

Mr. A. Nichols Moore: Table A gives a comparison of the average installation costs to an undertaking for single-heat control and three-heat control in cases where circulators are installed on the simple hire system in unlagged tanks, the wiring being carried out in lead-covered cable. This shows a saving of 5s. 7d. per installation in favour of single-heat control, which is an item to be considered when several hundreds of circulators are installed in a year.

The 3-heat circulator does not appear to offer any outstanding advantages, for the following reasons. Consider first the case where the circulator is switched on "low" (loading 750 watts). When the water is at the desired temperature, say 160° to 180° F., and a quantity of water is drawn off, the temperature of the water will not rise as it will be found that the dissipation of heat (losses caused by radiation and convection) is about equal to the input. Now consider the case where the circulator is switched on "medium" (loading 1 500 watts). No great advantage is to be gained from this control, as the loading is half full load and it will take approximately twice as long to heat up a given quantity of water; one might therefore just as well switch to "high," thereby saving time.

Table A

	Single-heat control	Three-heat control
	£ s. d.	£ s. d.
Materials	1 16 9	2 2 4
Labour	14 10	14 10
	2 11 7	2 17 2

The one advantage of medium heat is that it will give sufficient water for one bath if on for approximately 2 hours. Also, should the circulator be switched on "high" to prepare a bath for someone coming in at a certain time, and the bath is not required until half an hour or so later, the "low" switch is useful for retaining this temperature. Another advantage of 3-heat control which might possibly be considered is the ability to heat the water up to a predetermined temperature on "high" prior to retiring for the night, and leave it on "low" during the night, so that the water will be hot first thing in the morning.

I suggest that it should be the policy of a supply undertaking to charge consumers the extra sum involved if 3-heat control is desired, in the same way that some undertakings charge for additional benefits which can be obtained with other types of apparatus on hire, such as thermostatic control on a standard hire cooker.

I should like to refer to a difficulty which was met with in connection with the installation of a 12-gallon thermal-storage heater in a hairdresser's establishment, feeding 5 shampoo basins. It was found that there was an adequate supply when hot water was drawn off frequently and in small quantities; but if four or five shampoos were carried out in succession and there was a fairly long interval, say 30 to 40 minutes, before the next batch of customers required shampoos, the water was not nearly hot enough for this purpose. Apparently the hot water left in the tank, after that for the four or five shampoos has been drawn off, either mixes with the incoming cold water, thereby cooling the contents of the storage heater to such an extent as to render it useless for shampoo purposes (i.e. the recuperative period of the tank is too long), or a form of internal turbulence takes place, the cold-water feed pipe being so near the bottom of the heater that the cold water rushing in impinges on the bottom of the tank and sweeps upwards at the side. It would appear that the only way to overcome this difficulty is by installing a thermal-storage heater of larger capacity (say, 20 gallons) than appears necessary for normal use. There would then be a sufficient residue of hot water to combat the trouble.

The last question with which I should like to deal is the cause of the collapse of a hot-water cylinder in which an immersion heater had been installed. On making an inspection of the hot-water system it was found that there was a fairly long length of vent pipe in a horizontal position, and the theory put forward is that this vent pipe becomes a trap for the gases given off from the water during heating. When water is drawn from the tap this collection of gas or air is gradually drawn away, but in between draw-off periods the gases collect, and, should the water in the cylinder boil, the pressure from the steam thus formed exhausts the water from the cylinder up the cold feed pipe into the ball tank. When the pressure of steam in the cylinder falls, owing to the current being cut off, the return of cool water from the ball tank causes condensation and produces a vacuum. Then, if the cylinder is not strong enough to withstand the air pressure from outside, it will collapse. It is presumed that the cylinder collapse could be caused at any time, if sufficient heat were supplied from the back boiler; but as the immersion heater gives greater heat to the water the conditions become more apparent when it is in use. It would then appear that an installation of this sort should be provided with an adequate vent for the cylinder by installing a separate vertical pipe.

[The author's reply to this discussion will be found on page 50.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 3RD JANUARY, 1939

Mr. J. L. Carr: The title to the paper is a little unfortunate, because it conveys the impression that it deals only with the conversion of existing systems, and not with the application of electric water heating to domestic requirements. The ultimate aim should be to provide a continuous supply of hot water; this is not mentioned specifically in the paper, although in his verbal summary the author emphasized its desirability. In a paper on domestic electrification,* in which I collaborated some 11 years ago, I expressed the view that the most efficient manner of using electricity for the production of domestic hot water was to employ storage heaters at the points of utilization. That view I still hold. In actual practice, however, it is not necessary to provide a self-contained heater at each point; usually two or more adjacent outlets may be efficiently supplied from one heater. On the other hand, where there are long hot-water pipe-runs it is more satisfactory to provide independent heaters at the point of utilization. Incidentally, in a new installation this is the least expensive method. Where compact systems work in conjunction with fire-back boilers the existing hot-water cylinder may be satisfactorily replaced by an auxiliary storage heater.

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* *Proceedings of the Incorporated Municipal Electrical Association*, 1928, p. 161

Installations employing factory-made heaters are, of course, rather costly; and unless the supply undertakers have a reasonably attractive hire scale available some of the less affluent consumers cannot adopt the most efficient system. Moreover, in the North of England, small modern houses possess very little accommodation for separate heaters; and in many cases do not require continuous hot water—either because of cost, or because of the winter use of a coal fire. To meet these requirements for occasional use, a circulator-type immersion heater installed in the existing hot-water tank is useful, although not to be recommended in preference to the self-contained type. Circulators are inefficient as compared with storage heaters, even when lagging is employed. The circulator is not, therefore, suitable for the provision of a continuous hot-water service and should always be installed with hand controls, a thermostat being included for safety.

The variation in consumption of circulators is very considerable. In a limited number of cases examined, variations were observed from about 0·2 kWh to 16 kWh per day in different installations. The paper states that circulators are used principally in the summer months: in a number of cases, however, it has been found that greater use is made of circulators in winter. The characteristics of the circulator load are not well defined, but appear to be more akin to those of the radiator load than the storage-heater load.

Load characteristics are very important. In this country, partly owing to the operation of a large number of undertakers, a comprehensive survey on the lines of that carried out in the United States is not practicable. Records that have been obtained, however, give results very similar to those published in the N.E.L.A. Report. The latter should for a long time prove a very useful guide to those studying the subject.

The author mentioned the great potentialities of the hot-water load in improving the load factor of an undertaking, and showed slides indicating that load control during peak times will improve the supply load-factor to a very much greater extent than is possible if the load is uncontrolled. Although the water-heater load has been developed so far without any attempt at control in this country, the term "quite satisfactorily" should not, in my opinion, be used in this connection. Up to the present, undertakers have connected relatively few water heaters, and the effect is not yet pronounced. Only when water heaters are installed in much greater numbers will the effect be fully appreciated. I am convinced that ultimately the need for time control will be demonstrated. Approximately 35 % of the demand occurs during the time of maximum load on a system supplying mixed load, and where the load is primarily residential the effect may be even more pronounced. Future development will, I consider, necessitate the provision of means enabling the system load-factor to be kept under control, and likewise the cost of electricity.

A continuous domestic hot-water supply requires a large consumption of energy, and therefore the use of kitchen water heaters is to be recommended strongly. Nevertheless, according to information published on the Continent and in America, the consumption of electricity or gas for cooking is reduced in cases where electricity is used for water heating. Figures recently published regarding the Winnipeg supply show that this reduction amounted to as much as 35 %. Where, however, a full electric hot-water service is given, the value of the increased consumption far outweighs this disadvantage.

(*Communicated*) Since the meeting, numerous references have been made in the technical Press to abnormal domestic-load peaks resulting from cold-weather conditions, and their effect on costs. These references have given added significance to the importance of load control for those items of load amenable to treatment.

Mr. L. H. A. Carr: I strongly disagree with the author's remarks on page 3 where he states that it will take a 4-kW geyser 1 hour to heat enough water for a bath. Neglecting losses, 27 gallons of hot water would be supplied in this time, which is much more than is necessary. On making a test of my own bath recently, after drawing a normal amount, I found that the depth of water in the centre of the bath was $5\frac{7}{8}$ in.; after getting in, I found that the level had risen to $8\frac{5}{8}$ in. The quantity of water was 11·2 gallons, which corresponds to a temperature-rise of 46 deg. F. when 3 kW is applied for half an hour, and this costs $\frac{3}{4}$d. when power is obtained at $\frac{1}{2}$d. a unit. This amount of hot water, though not extravagant, is as much as is usually obtainable from the old coal-fired system in an average house, and it is spoiling our case to quote higher figures. In fact, later on in the paper (page 7), the author himself quotes 10 gallons for each hot bath!

I think that the author makes too much of lagging. A hot cylinder cupboard has many advantages, while any heat which escapes from it is not wasted but helps to warm the bathroom, and also, to a small extent, the house generally; while the addition of lagging must necessarily increase the first cost of the installation.

On page 11 the author suggests that in a converted system the solid-fuel heating can be "relied upon" in the winter months. It is my experience that the electric water heater is just as useful, and used nearly as much, in the winter months as in the summer, since the kitchen fire, being used for other purposes in addition, does not give the quick replenishment of hot water which one has become used to in the summer, and consequently the electric heater is switched on again.

The author states on page 10 that hand control is suitable for working-class consumers, but that more well-to-do consumers should be provided with lagged automatic systems. In my own house, however, experience has shown that hand control is perfectly satisfactory.

Referring to Fig. 10, I would ask the author what modification is recommended where there is no storage cylinder, as was the case some years ago, and may be still, in the majority of houses on the North-East Coast.

Mr. O. Howarth: The author's second slide showed that the standing loss was less when the storage cylinder was used than when the water was drawn off. This applies particularly to the circulator type of heater where the lagging is not very good. Most of the electric water heaters installed in this district are of the circulator type.

I should like to emphasize that one gets much better service from a water heater with a high loading than from one with a low loading. In houses where the water storage is insufficient for the requirements the service can be improved by increasing the loading.

Another reason why there is much to be said for higher loadings is that when people hire a water heater they are influenced far more by the relatively higher charge for the larger sizes than they are by the amount of water which the salesman may think they are going to use, and they will tend to select a water heater which is too small if it is to work on the storage principle. So unless the loading is high the service is unsatisfactory, and ultimately the water heater may be thrown out.

On page 7 the author refers to a water heater which will give three or four good hot baths during the day, provided there is a minimum interval between them of 2 or 3 hours, dependent upon the exact sizes of heater and bath. A heater of this type will have a rating of 1·5 kW and a 12- to 15-gallon cylinder. The time can be reduced to 1 to 2 hours, however, by installing a 3-kW heater. There is no reason why supply undertakings should be diffident about connecting 3-kW water heaters, seeing that they cheerfully connect 6-kW cookers.

Even with self-contained heaters more use might be made of the circulator, which has the advantage that the hot water collects at the top of the cylinder rather more rapidly, and there is also the benefit of the reduction of losses.

Fig. 6B is interesting, because the design of a circulator is a matter which seems to receive very little attention, judging by the rather curious performance of some of the circulators offered to supply undertakings. Some of them only warm the water in the upper part of the cylinder, while some which warm the whole take a long time before any warm water can be drawn. It is necessary to get a good compromise between quick heating of the water at the top of the cylinder and a fairly even temperature down the length of the cylinder. Designers offer various arrangements, some even going so far as to have a special switching arrangement in order that the consumer may be given just the service that will be most suitable for him. I think it is better, however, to give a fairly good average service and offer the same facilities to all customers.

On page 8 the author appears to suggest that circulators are usually hand-controlled and are without thermostats. I think most people lag their cylinders and fix thermostats, and it is the custom of my undertaking to fit a control switch also, so that hand and automatic control are provided. The advantage of incurring the small cost of lagging is very considerable, and it is surprising how much better a lagged cylinder performs when operated from a fire-back boiler. Lagging is an advantage too when airing is required, as in a linen cupboard.

With regard to restricting the supply so as to improve the load factor and thus be able to offer a lower price, we have built up the water-heating business without any restriction, and when consumers are making considerable use of it because of its great convenience we can offer them time switches or other devices in order to help to level the load curve, with an appropriate reduction in costs. With the ordinary usage of water, even if the price is reduced by about one-third, the saving will not as a rule pay for the necessary control apparatus.

We are apt to overlook some of the many uses to which the ordinary wash-boiler can be put. It is an economical alternative to some of the hand-controlled unlagged high-price devices which are on the market.

Mr. W. E. Swale: One can note from Table 2 the deplorable fact that 71 % of the families in this country are living on £250 a year or less. This has an intimate bearing on the development of electric water heating.

With regard to lagging on the ordinary domestic cylinder, 2 or 3 years ago I was a little doubtful, and did not want to suggest anything which would put up the cost. I am now quite convinced that we should use lagging: the cost is small, and the benefits considerable. Many people appreciate that a lagging jacket is doing good in the winter when they are not using the electric heater, and this is an extremely good selling point.

The author makes out a good case for the water-heating load from the supply authorities' point of view, but it is not until practically the last sentence of the paper that he mentions the satisfaction of the user. I think more might have been made of this. In these parts we deal with a lot of poor people living under most distressing conditions of discomfort. It is a source of delight and satisfaction to them when, for the first time in their lives, they can have a reasonable supply of hot water. The "appreciation value" of electric water heating is probably greater than that of any other domestic service.

In connection with the installing of electric water heaters, there is a point on which I should like the benefit of other engineers' experience. We have insisted, from the beginning, in putting in 3–4 ft. of asbestos-covered fireproof flexible between the circulator top and the junction box inside the cupboard. Where the back boiler works well the water in the cylinder approximates to boiling point for long periods. We have a feeling that if ordinary tough-rubber-sheathed cable is used in this situation it is liable to perish, and give trouble in years to come; the slight extra expense of running asbestos-covered flexible from the terminal to the circulator is probably justified.

With regard to the wider aspect of the paper, I am a little disappointed that the author has not opened his heart to us a little more. Why, for example, has the curve of development risen so much more rapidly in this country than in France and Germany?

The main question is, how are we going to sell more water heaters? In Manchester we sold about 2 300 in 1938, and thought we were doing very well; but there is a potential sale of about 100 000 water heaters in Manchester, and we have not yet connected the first 10 000. How are we going to get the remainder of the business? By bringing down the hire charges? If we do, is the electricity supply industry going to foot the bill? Other industries have not allowed themselves to be burdened in that way. If the water-heating business is to achieve rapid development, and our load curves are to be substantially influenced, we may have to offer still lower hire charges, and practically free installations. In that case we ought to consider, before starting, how the cost is going to be met.

Mr. A. C. Eden: I agree with Mr. Swale that, as regards existing properties, it is a problem to decide who shall pay for the water heaters which we desire to see installed. As regards new property, however, an effort should be made to get the builder or landlord to put the water-heating appliances in.

Mr. A. R. Chorlton: With reference to the author's slide illustrating an immersion heater installed in a cylinder fitted with a calorifier, there is a distinct possibility of electrically heated water circulating through a domestic boiler to such an extent that if the thermostat is set at 165° F. it is doubtful whether it will ever switch off. A check-valve adjacent to the hot-water system in the radiator outlet should certainly be installed in order to prevent circulation.

It appears to me that there is room for improvement in the design of electric water heaters, particularly the self-contained models. If the water connections could be made at the back of the $1\frac{1}{2}$-gallon model so that piping could be taken flush up the wall to the water heater it would avoid the usually unsightly connection at an angle of 45° from the wall face to the centre of the water heater, which is usually some 6 in. away from the wall.

Fig. 2 shows a marked increase in the number of water-heater connections made in this country during 1937, and it would be interesting if the author could relate these in any way with publicity and propaganda work done by the British Electrical Development Association.

I should like the author's opinion as to whether the thermostat should be set and sealed at a temperature of 165° F., since in some cases consumers are inclined to alter the setting to such an extent that at the end of the quarter complaints are received as to excessive consumption.

Mr. W. Wallwork: On page 1 the author states that the usual allowance made in designing fuel-fired domestic hot-water systems is 40–50 gallons of water at 150° F. for the day's supply to an average small house. That figure is not realized in our experience around Manchester.

Regarding the tinning of the containers of small heaters, a consideration which the author takes into account is that of the purity of the water for drinking purposes. Another consideration which is important, particularly in soft-water districts, is the presence of acid in the water. This acid will act on untinned containers, shortening their life considerably, and increasing maintenance charges.

With regard to heat losses and the lagging of cylinders, we have some interesting figures actually taken on installations in this district. In quite a number of cases the cylinder is not fixed in a cupboard, but in an exposed position in the bathroom or kitchen. If the cylinder is fixed near a wall with a northern aspect the losses are in the region of 1 000 watts, so that with a 2-kW circulator (which is fairly standard), for every 2 units of electrical energy put into the cylinder 1 unit is lost. If, with effective lagging, the loss can be reduced to the region of 400 watts, the heating time will be reduced by one-third, irrespective of any reduction in electricity used. A further selling point of electric water heating is that the jacket provided along with the heater improves hot-water supply when the domestic coal fire only is in use during the winter.

I disagree with Mr. L. H. A. Carr when he deprecates the tendency of electricity supply authorities to reduce as far as possible the number of units used by consumers on their water-heating installations. No other electrical service can be so expensive when misused, so that if the misuse can be kept to a minimum by attending to such matters as lagging and layout, there is more likelihood of rapid expansion in the future.

Mr. G. H. Sammons: In this part of the country electricity supply engineers are fortunate because the water is suitable for heating by electricity. In other areas, however, it is almost impossible to use this type of apparatus, owing to the hardness of the water, and much more research will have to be carried out before the hire and maintenance of these heaters is a reasonable proposition.

In the north of Lincolnshire the public water supply is pumped up from a chalk bed about 100 ft. below the surface, and of course the water is very hard. A curious condition was often observed when a circulator was put into a hot-water tank. If the water was heated entirely by electricity and the fire-back boiler was not used, a certain amount of scaling took place. If, however, the circulator was used and the water heated partly by electricity and partly by the fire-back boiler, the scaling was observed to be much worse. I should like the author to give a possible explanation of this.

Mr. Swale asks how we can sell more water heaters. All the plumbers in the town of Blackburn were invited to a comprehensive demonstration of practical examples of electric water heating, as it appeared obvious to us that no great strides would be made in this direction without the help of the plumbers. Further, builders are encouraged to incorporate in new houses fittings that will facilitate the installation of water-heating appliances. It is a definite brake on development when newly completed houses have to be mutilated in order to install apparatus that should have been incorporated in the original design.

Mr. H. A. Gray: I do not agree that "the use of hot water depends primarily upon personal habit" (page 2). Generally speaking, the use of hot water in the home and even in industry depends upon the cost; this is particularly the case when the water is electrically heated. It is too frequently forgotten that electric water heating, when correctly installed, provides a solution to the heat-loss problem, which no other form of heating can do. The figures given in Table 1 do not go far enough; in private houses only about 5 % of wash hand basins use $1\frac{3}{4}$ gallons.

The figure given on page 3 for the hot-water output of a 4-kW geyser is not accurate; assuming the efficiency given on page 2, the figure should be 0·4 gallon.

One cannot agree that a British Standard Specification is about to be issued owing to designs having become stabilized. Surely the Specification has been prepared to limit the number of sizes for the three more general types and to prescribe the gauge of containers, fixing dimensions, pipe sizes, and loadings. The Specification gives tests of minimum performance which would be demanded by the purchasing engineer in any event.

The majority of containers are not hot-dipped; quite 50 % are made from rolled tinned sheets. Tinning may not be necessary in hard-water districts; it is essential in soft-water districts. In tests carried out by the late Prof. Delapine over 20 years ago, small animals were poisoned when continuously fed with soft water from plain copper tanks.

It is not correct to state that all heaters larger than 5 gallons are fed from ball-valve cisterns. In the North Midlands it is standard practice to connect all non-pressure heaters (with a non-return device) to the cold-water main; the water from these as well as from self-contained cistern-type heaters (made up to 30 gallons) is suitable for culinary purposes.

Surely the principal factor governing the watts loading of a heater is the recovery period. A recovery period of 40 to 60 minutes is satisfactory in the smaller types if they are of adequate water capacity. With time-switch-controlled storage heaters 1 kW per 10 gallons will cope with the water maximum demand if the heaters are of adequate storage capacity.

The section of the paper dealing with thermostats is incomplete. Research work which I have carried out proves that the design of the heating elements is of more importance than the differential of the thermostat.

The heat losses given in Fig. 3 can only be correct for a certain mean water temperature; an alteration in one of the factors just mentioned would vary the curve considerably.

Small heaters can only be connected by means of a T-piece where a screwed-backplate tap is installed: there must be half a million houses without this type of tap. Restricting washers should not be allowed; an external adjustor not incorporated with the tap enables the heaters to be used in any area. The author's statement in regard to the head of water required for cistern heaters is only correct for the constant-volume type.

The results obtained with the thermostats to which Fig. 6B relates are entirely inadequate for the scores of thousands of post-War houses with small cylinders. I use two types of circulators which give a maximum temperature-difference of only 22 deg. F.

In regard to the figure given on page 9 for the reduction in watts loss for lagging jackets, the author does not state the temperature at which the test was taken. At certain thermostat settings it is impossible to reduce the watts loss to 125, on a 36 in. × 14 in. cylinder.

It is pleasing to note the stress the author places on the fact that the provision of an electric towel rail is more economical than omitting lagging on a cylinder. Such things, however, are expensive to purchase. I usually recommend a short length of tubular heating fixed in the airing or cylinder cupboard; but this cannot be used if the cupboard is packed with loose cork, an undesirable recommendation.

Mr. J. Lee: On page 3 the author states that the total number of self-contained heaters in use is greater than the number of immersion heaters; this is not typical of experience in this area. Of the last 460 installations carried out by my company, 26 % were 0–5 gallon self-contained heaters and 74 % circulators. Possibly the high number of self-contained heaters in use is accounted for by the policy adopted by some supply authorities of supplying a $1\frac{1}{2}$-gallon self-contained storage tank as part of its cooker hire scheme.

Regarding the question of heat losses, mentioned on page 5, I should have liked the author to have shown a curve giving the watts loss in respect of various temperature settings on the thermostat. In Lancashire a big proportion of the domestic hot-water cylinders are very limited in capacity, and consumers are tempted to set the circulator thermostat a little higher than is recommended; increasing this setting may be responsible for increasing the watts loss by as much as 25 %. On reviewing 300–400 installations where a circulator has been fitted into the domestic hot-water cylinder I find that 20 % of the cylinders were of 12-gallon capacity and 45 % of 20-gallon capacity.

I am surprised to find that the author does not object to people drinking the water from a self-contained heater. One view of the interior of the tank and the deposit on the apparatus plate of such a heater after 12 months' service on the mains of some rural water supply is sufficient to turn people away from this practice.

I should have liked the author to have criticized in a constructive manner some of the automatic circulators available in the water-heating market. I have met some circulators where it has been impossible to put more than 2 units of electricity into the domestic cylinders without the thermostat operating and cutting off the supply.

Mr. N. Ashton: There is in this part of the country a class of consumer requiring special attention—the occupier of the cottage type of property where there is no hot-water system installed. From the point of view of such a consumer the installation of a cistern-type storage heater proves unsatisfactory, for the following reasons: (1) High initial cost of installation. (2) Failure to obtain small quantities of water in a short period of time. (3) Long recuperating period required for successive baths.

There is a heater available which fulfils these requirements, and it is designed along the lines of the Rolyatt cylinder. Has the author had any experience of this heater, and, if so, does he consider that it offers a solution to the above problem?

Mr. W. V. Butterfield: I should like to challenge the author's remark that this subject is simple. I do not think it is, either from the point of view of the manufacturer or from that of the designer of the installation. There are a multiplicity of problems to be considered, some of which are not fully solved, such as the question of anti-drip devices and hard water; the latter problem does not arise in Manchester.

The publication in America of the N.E.L.A. report has perhaps resulted in an undue orientation of the British outlook. It will probably be worth while for British supply authorities to consider doing some research similar to that done in America, in order to ascertain the effect of various loadings in water heaters.

Mr. W. Fennell: Those who have to deal with water heating should see first that there are no leaky taps or undeclared taps on the installation. A short time ago the owner of a large house reported that an excessive amount of electricity was being used for water heating. It was discovered that there was a tap in the housekeeper's cupboard which had been leaking badly for several months, and possibly for years. When this was dealt with, consumption returned to normal. One should also see that the draw-off pipes and the hot pipes are not in contact. Two copper pipes in contact will transfer a large amount of heat and reduce the efficiency of the installation. Another point is: use the plumber. He has access to all houses, and his views have considerable weight. It is good policy to employ him for the plumbing involved in the installation of electric water heaters.

Mr. H. C. Crews (*communicated*): No mention has been made in the discussion of the contribution to the smoke abatement problem which the rapidly increasing use of electric water heating must be making. Fig. 1 indicates that in this country nearly 400 000 coal or coke fires can now be shut down for long periods, if not entirely. Many of these are kitchen fires, which have previously consumed quite half the domestic coal purchased, and admittedly, in bulk, are the worst offenders against atmospheric purity.

In these days of ready-cooked foods, tinned and otherwise, and now that so much domestic cooking is done by electricity or gas, numerous kitchen fires have become mainly very inefficient hot-water providers. In houses of £40–£50 rateable value where we have provided a 1-kW kitchen fire as an alternative to the coal one, and adopted electric water heating, a saving averaging 10 tons of coal per annum has been effected. Summer electric fires in living-rooms have contributed to this saving, but electric water heating has been the largest factor. The small electric kitchen fire usually has a horizontal element which accommodates two medium-size pans for minor warming and cooking, such as porridge, egg boiling, etc. A similar 1-kW element, but fixed vertically, in the same electric fire and switched separately, may be included for room heating when required. Most small kitchens, however, except at odd times, are too hot—particularly where gas is used for cooking.

Continuous hot water is a pleasant luxury, but comparatively few households can afford it. Self-contained lagged electric heaters of small capacity are quite reasonably economical, and water drawn from them is safe for drinking and culinary purposes.

Fig. 2 shows that there are over 150 000 immersion heaters installed in the United Kingdom; I hope that the majority of these are not merely single-wound circulators let into existing cylinders of ordinary house water systems; but such is, I fear, the inadequate apparatus which is being largely hired out to householders by the supply authorities, mainly as an "easy" proposition. Supply engineers may hope to improve their load factors and outputs by this means, but soon the consumers wonder why the circulators boil, why the amount of hot bath water is inadequate, and why accounts are so very much higher. If thermostats are added, for an extra hire charge, they may stop boiling and cause some reduction in the electricity account, but hot baths will now be still more difficult to obtain. That many such primitive arrangements have needed improvement by the insertion of an extra immersion heater near the bottom of the cylinder is proof that the trouble exists and is serious. I feel sure that either a double-wound circulator such as is shown in the lower diagram of Fig. 7, or two ordinary immersion heaters, must as a minimum be used in all hot-water adaptations of this sort, if general and final satisfaction is to be given.

The average consumer does not need to have a full cylinder of hot water, with its attendant heavy radiation losses, available during 24 hours daily, and he will not ultimately pay for such excessive consumption. A few gallons of hot water constantly available for basins and kitchen wash-up, with a full cylinder of hot bath water obtainable at 2–3 hours' notice, is the best scheme for the average consumer, and the most he will generally be able to afford in extra consumption of electricity. I therefore strongly support the plan of combining thermostatic control of a top heater (1 to 1·5 kW) with hand control of a bottom one (1·5 to 2 kW). With such a system installed in a 15- to 20-gallon cylinder, a full hot bath can be obtained economically in 2 to 3 hours, according to the initial temperature of the cold water.

A useful refinement is the double-wound immersion heater using series-parallel hand control for the bottom heater. This can be switched on as an occasional heat booster in cold weather, or, after a late-night bath, left more or less on (with the top heater) so that an early-morning hot bath is also obtainable.

For cylinders in linen cupboards, it is questionable whether lagging is an advantage. Most housekeepers will object to temperature reduction in linen cupboards.

[The author's reply to this discussion will be found on page 50.]

NORTHERN IRELAND SUB-CENTRE, AT BELFAST, 17TH JANUARY, 1939

Mr. F. Johnston: I should like to know the number of electric water heaters installed in Ireland and the relative numbers installed in Northern Ireland and Eire.

The author states on page 3 that if the density of the heat transmission through the surface of the heating element can be reduced to 10 watts per sq. in. of surface, scaling is slight. Is this figure of 10 watts per sq. in. measured on the surface of the tube containing the heating element, or at the surface of the heating element itself?

Regarding heat insulation, I should like to know whether the author has had any experience of the use of glass wool, which is available for lagging purposes.

On page 4 he uses the expression "recuperation period." I am not quite clear what he means by this, and should like him to explain the difference between "recuperation period" and "charging period."

Table 4 gives the number of pints of hot water used daily in a household, but does not state the number of people in the household. I should like to know the average daily consumption in a household of, say, four persons.

Mr. F. W. Parkinson: One important problem which demands attention is that of the protection of the electrical connections between the switch controlling the heating element, the thermostat, and the element itself. Something should be done to produce a 3-heat switch in combination with a thermostat, or to protect properly the conductors passing between them.

The author mentioned the use of a gate valve for switching over from one source of heating to another. I am of opinion that valves on a domestic hot-water system are unsatisfactory and that their use should be discouraged. A domestic hot-water system should be entirely automatic.

Mr. J. Finlay: The author's first slide showed a 12-gallon heater with two hot-water draw-off branches, one taken through the top and the other through the bottom of the heater; it would appear that the incoming cold water is likely to have a cooling effect on the hot supply drawn through the bottom of the heater. Would it not be a more efficient arrangement to draw all hot supplies through the top of the heater?

The arrangement shown in Fig. 10 is typical of the hot-water supply systems installed in a very large number of small houses, except that the "lazy" pipe C is not fitted and the primary flow from the cast-iron boiler is connected to a higher position in the cylinder. As there is no room in these houses for separate local heaters, a very large field is available for the development of electric water heating by the introduction of a thermostatically controlled circulator, as shown at D, provided a quick supply of hot water for washing and bathing can be obtained from cold in the early morning. For this purpose it may be necessary to have, in addition to the circulator, a hand-controlled immersion heater fitted near the top of the cylinder.

Mr. H. C. MacEwan: On ships, increasing use is being made of electric water heating for providing supplies of domestic hot water. In recent years five coastal vessels have been built in which the whole of the domestic water-heating on board is carried out electrically, storage tanks of 300–400 gallons capacity with circulators of 45 to 65 kW loading being fitted. These have proved successful over a period of 10 years. On board ship, electric water heating is applied principally with the object of eliminating long lengths of piping, and two kinds of water heaters are required: first, those to supply wash hand basins and baths in hospitals and other places remote from the centre of the vessel; and secondly, those for the supply of boiling water for tea-making and cooking. The first type are those described in the paper; the second are of the geyser type, designed to give boiling water only, thus preventing stewards from making tea with water which is not actually boiling.

I am particularly interested in the self-descaling element, but do not quite understand the method of preventing scaling by making "the heating element so long and so thin and of such a shape that its expansion and contraction during heating and cooling is sufficient to fracture and throw off the deposit of scale." More information on that point would be welcome. On ships it is important that the heating element should be self-descaling and should be easily repairable in foreign ports.

The author points out the difficulties of securing an even action of the thermostat. Is it not advisable to fit it horizontally?

Mr. E. N. Cunliffe: A distinctive feature of the water heating load and one which is not shared by most other types of load is the inherent thermal-storage effect, which enables the load current to be switched on or off at will within certain limits without affecting the efficiency of the hot-water service. To distribution engineers this is a very welcome feature and promises to become a most useful means of raising the system load-factor. For instance, the author's load curve for Basle indicates that the water-heating load during the night is very steady and is nearly as great as the ordinary domestic and industrial peak load during the day.

This effect may be obtained by restricting the hours of use by local time-switch control or by remote carrier-current control from the power station, and other similar methods, all of which, however, have the disadvantage of imposing a restricted supply. On the other hand, it is common practice in Britain to give an unrestricted supply for water heating, and although this may be satisfactory from the consumer's point of view, it does not enable a supply authority to make the best use of the possibilities of the water heater as a perfect load-levelling device.

As a compromise between these two methods I suggest that a completely unrestricted supply be given but that the consumer be persuaded by financial inducement to use the apparatus mostly during times of light load on the undertaking. This could, perhaps, be attained by installing in series with the main meter an additional meter incorporating a time switch and designed so that it would record only those units used during certain predetermined intervals during the 24 hours. For each unit so recorded a discount could be allowed, and in fact the dials of the meter could be calibrated to show the discount in shillings and pence. Such an inducement would probably have the desired effect on the majority of consumers, who would in time become voluntary load-levellers for the undertaking.

Mr. J. S. Scott: The author refers to the scaling difficulty, and the various methods of overcoming it. It occurs to me that if the heating element was mounted in a tube made like a Bourdon gauge it would expand and contract, thus shedding the scale.

Mr. S. S. Galloway: Do anti-scaling devices stop the formation of scale, or just dislodge it so that it falls to the bottom of the heater? Scaling takes place at a high temperature, and the only way to retard it is to keep the watts density on the element casing low.

Is it not true that if a circulator is installed reaching below the fire-back boiler flow and return pipes on the hot-water cylinder, circulation through these pipes is likely to occur?

[The author's reply to this discussion will be found on page 50.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 23RD JANUARY, 1939

Mr. F. D. Parker: I am somewhat disappointed with the paper in that it does not add anything new to the information previously available. In my opinion it would have been more helpful if reference had been made to the comparative costs of different types of installations, and to the application of other types of water heaters for conversion purposes, e.g. flexible immersion heaters, external circulators, and tank belts—which are very useful in hard-water areas.

It is correctly pointed out that two households equipped with similar hot-water systems may use very different quantities of hot water. Other factors which influence hot-water consumption, and therefore running costs, are varying sizes of hand-basins and baths, also heat losses and wastage. It is self-evident, therefore, that attempts should not be made to compute running costs to any considerable degree of accuracy for the purposes of furnishing consumers with estimates, as such figures might prove very misleading. For this reason separate metering of water-heating apparatus would also appear advisable.

I cannot agree with the author that in soft-water areas thermostats may be safely set to give draw-off temperatures of 190° F. In households with young children such a high temperature would seem dangerous from the point of view of scalding, apart from the possibility of cracking hand-basins. A draw-off temperature of 150°–160° F. is usually adequate for general domestic requirements; with such a figure heat losses are reduced, and although there is a slight reduction in the actual heat stored this can be counterbalanced by increased capacity and loading. It would be interesting to know what thermostat settings and thermostat differentials the author would recommend for conversion installations operating in conjunction with fuel-heated boilers.

The standardization of inlet and outlet sizes and fixing centres of wall-mounted storage heaters has simplified installation and service work, but I am uncertain whether the loadings of 12- to 30-gallon heaters as given in Table 3 are not too low, bearing in mind practical considerations. The average bathroom is relatively small and often there is no room for the accommodation of a 20-gallon heater, whereas a 12-gallon size loaded at approximately 3 kW and controlled by a 3-heat switch would often suffice for the requirements. It seems somewhat inconsistent to restrict storage-heater loadings to an absolute minimum and yet permit 3-kW heaters to be fitted to existing 20-gallon circulating tanks. A better arrangement might be to restrict loadings of immersion heaters when fitted to large-capacity existing tanks, thus ensuring that the heaters are in almost constant operation. Provided the consumer is advised of the heating capacity of the apparatus, no difficulty should arise.

I agree with the author that a circulator having the bottom section of the draught tube cut away, as illustrated in Fig. 7, is a distinct improvement on previous tubes; also that for large tanks in hard-water areas two horizontal immersion heaters, one fitted at the top of the tank and the other at the bottom, is a satisfactory arrangement, as maximum heat storage is obtained. One difficulty is, however, that the whole of the tank has to be drained for the fitting of replacements, whereas this is not the case when circulators are used. The thermostats controlling the immersion heaters should also be mounted in the same plane as the heaters and not above, otherwise a substantial amount of scale is apt to accumulate on a thermostat tube.

I do not agree with the fixing of immersion heaters in calorifier tanks, owing to the high heat losses usually experienced and the possibility of damage to the calorifier tubes when the heaters are being fitted. If a heater is required then I would recommend a tank belt.

In regard to electricity supplies to hotels, blocks of flats, and commercial premises generally, I am interested in the data given in Table 8 and especially in the hot-water requirements for shower baths. Has the author any further information in this respect, especially in relation to the type of shower fitments used? Further details of the hot-water requirements for blocks of flats, both of the working-class and the luxury type, would also be welcome. For such buildings, hot-water supplies from a centralized storage chamber are generally cheaper and more economical than the use of separate storage heaters, energy being supplied during off-peak hours at a cheap rate. A good arrangement is to install two or three large storage tanks in different parts of the building, feeding a selected number of draw-off points. In this way installation costs are often reduced, and any wastage on one section does not affect the other. For the control of electricity supplies to such installations the carrier-current system offers many advantages over time-switch control, owing to the uncertainty as to when the peak load may actually occur in many areas.

Mr. P. Ward: From experience one can sense what the consumer's hot-water requirements really are, instead of calculating it from the consumer's own impressions and statement of the quantity of water used. Lavish users are inclined to under-state and careful users to over-state their requirements. Where actual requirements can be ascertained, quite remarkable results can be obtained. I know of a 1-kW heater in a 50-gallon cylinder, installed 15 years ago, which has shown a regular consumption of over 7 000 units per annum, all off-peak. Incidentally, not a single service call has been necessary during the whole of that period.

I agree with the figures given in Table 1, except those of 25 gallons and 4·5 units per bath, which are too high. The average present-day bath only needs 3 to 3½ units. Baths are shorter than they used to be, and have long sloping backs and semi-elliptical cross-sections, instead of practically square cross-sections. Moreover, regular bathers do not have a bath full of water. It is only the occasional luxury bath which is full.

Turning to page 3, I consider that the statement that certain types of elements crack off the scale by reason of expansion and contraction, is not very well founded. It depends largely, of course, on the nature of the scale, and with some types of water there may be considerable crack-off.

In my opinion hard water does impair the efficiency of electric water heaters, as more heat is conducted from the heat-locked element to the baseplate, and thus lost. Nevertheless, this amount of heat is not comparable with the increased losses due to scale on fuel-fired boilers.

I consider the loadings shown in Table 3 to be higher than are really necessary. We use loadings equal to only two-thirds of those mentioned. Our heaters, however, have three element pockets, of which only two are normally used. The third element is added when necessary, but such cases are rare.

As regards the author's remarks under the heading "Thermostat," I would mention that we keep our thermostat settings down to 160° F. in hard-water areas.

Attention should be drawn to the error, often made in calculating heat losses at maximum temperature, of overlooking the fact of temperature gradation and recuperation periods. During the latter time a large proportion of the cylinder contents are at temperatures much below the maximum.

In this area the water authorities do not allow the fixing of feed tanks in the roof. Such tanks must be below the ceiling level, and this reduces the available head, and often presents difficulties in bathrooms. Do the author's remarks on pressure-type heaters (page 5) mean that safety valves are definitely prohibited? I am not aware that this is so, but I agree that they are undesirable, and I never use them.

The kilowatt-hour figure given in Table 4 is confirmed by readings which we took on a series of heaters in 1928, when the average for sink heaters was found to be 2·6 units per day.

The designing of a good anti-drip device still presents a problem. The sliding sleeve shown in Fig. 5 is new to me. It seems as though it should be satisfactory in soft-water areas, but I should be doubtful about it in hard-water areas.

Referring to the remarks at the bottom of col. 2, page 7, I prefer to fit thermostats at the top of the cylinder so as to be in that part of the water which is the first to be drawn off, but they should not be in the same vertical plane as the heater.

In cases where two elements are fixed in the manner suggested on page 9, there is not much chance of the upper element cracking off its scale due to any possible expansion and contraction, as it is always surrounded by hot water rising from the lower element; and it will be the first to fail in hard-water areas.

In selecting the position for the water heater, losses from the expansion pipe should not be overlooked. This pipe contains the hottest water for the longest periods, and even though internal circulation may be reduced by some form of heat trap, conduction losses are still high.

I do not agree with putting a heater into a calorifier (see page 13). Losses by circulation round the heating coil and boiler and also by conduction to the metalwork of the radiator system are very considerable.

Were the consumption figures for clubs, given in Table 7, obtained from actual experience, or were they estimated? I have no figures to check them with, but they seem to me to be high.

Turning to page 17, I would point out that actually there is not a great deal of diversity in bathing times: the majority of baths are taken late at night. If geyser-type heaters were used, the average running time for a bath would probably be 20 minutes, so that there would not be a greater diversity than 3.

Change-over switches are very undesirable. The times when cooking is heaviest are also, generally speaking, those when the hot-water demand is heaviest, e.g. when guests are being entertained. Some type of carrier-current control, as referred to on page 19, offers the most likely solution theoretically, but it is costly unless the number of water heaters connected on any one network is large.

Mr. W. Cross: Very little is said in the paper regarding the attitude of the user. I believe that the user does not worry to any great extent about efficiency, but that " electric hot-water " has been put in in very many cases because of its availability at all times, particularly in the early mornings.

I suggest that, from the user's point of view, with some types of heaters the period of the heating is somewhat long. This can, I believe, be got over by putting an additional heater on the water boiler under hand control; but would it not be better to increase the loading on the standard water heater, so as to reduce a 4-hour recovery period to, say, 3 hours?

I suggest that the diversity in time of use of the heaters would be such that increasing the loading of heaters by 50 % would have a very small effect on the maximum load of the system. In the mornings some people start their water heating at 6, others as late as 9. In the evening the maximum load may occur as early as 6 if there are children, and in other cases at any hour from 6 to midnight. I therefore think that from the user's point of view it may be useful to consider whether the loading of water heaters should not be increased.

Mr. E. C. Lennox: One outstanding feature which is made evident by the paper is the great diversity in the use of hot water in different homes. There is no rule-of-thumb method which can be used for assessing the requirements of various houses, but the consumption of hot water must depend upon several factors: First, the income of the house; secondly, the number of persons normally living in the house; thirdly, the habits of those persons (number of baths per week, and so on); fourthly, the layout of the hot-water system. Perhaps a fifth factor can be considered—whether or not the household has a domestic servant; domestic servants are frequently wasteful of electrically heated water. Electric water heating is successful because of its high running efficiency, and it is therefore for the specialist to ensure that only apparatus suited to the particular household is installed.

It would be a pity if the reader were left under the impression, as indicated on page 1, that north of the Trent hard water is scarcely known. Hard water is supplied from wells to South Shields and Sunderland, and I believe the hardest in the country is at West Hartlepool. Whether the water is hard or soft, is not 190° F. too high a draw-off temperature? Such a figure surely means high losses, less efficiency (due to heavier pipe losses), and a temperature which is too high for normal use. I note that the author calculates most of his efficiencies on the assumption of a draw-off temperature of 150° F.

I am of the opinion that builders should be induced to lag all hot-water cylinders in new houses, whether or not electric water heaters are to be installed in the first instance, having in mind the fact that it will be a step towards the introduction of the electric water heater at a later date. Further, if a standard form of flange could be fitted to circulating cylinders in new houses an important step would have been taken in the introduction of electric immersion heaters.

Coal fuel as an alternative must be cheap to allow for the losses attending the coal-fired fire-back boiler type of hot-water apparatus, not only from unlagged storage cylinders but also in the stoking of the fire. The cheapness of coal for this purpose is surely a fallacy; how often has one seen coal fires being blazed away merely to heat the water boiler at the back?

Water heating is looked upon by many as one of the last uses of electricity to be considered in the development of the all-electric home, whereas it should be one of the first. I should hesitate to agree with the author (page 17) that it is " the best of all domestic applications of electricity." It is certain that the installation of electric water heating, if only for summer use, obviating as it does the need for the kitchen fire during the summer time, is quickly followed by the installation of an electric cooker. With an efficiency of 93·5 % (page 5), which is much higher than that of competitive equipment, and, moreover, can be maintained in comparison with other types of water heating equipment, electric water heating at the normal price obtaining throughout the country becomes an economic proposition for the majority of households.

I think the paper could have been very usefully enlarged by the inclusion of efficiency figures for the more common types of competitive installations—coal fires, gas heating, and so on. Such information could not help but be useful to the man who has to make contact with the consumer. Reference might also have been made to band- or belt-type heaters, which have relatively high efficiencies and have the additional benefit of being easily fitted, and easily removed.

One salient feature of the electric water-heating load is its value as a means of filling up the valleys in the normal load-curves of supply authorities. It is also capable of being controlled so as to avoid its use at peak-load times, and this can be arranged without affecting the efficiency of the system installed. Unfortunately the cost of such a system of carrier-current control could not be met solely for the purpose of controlling water heating, and if supply authorities wish to control water heating by this method consideration must be given to the switching of street lighting, A.R.P. signalling, and so on, so as to obtain from these other uses their share of the capital commitments.

Mr. K. Patton: One of the author's slides showed a circulator fixed below the level of the cold feed and flow pipe from the boiler. I have found that it is better to have the bottom of the circulator pointing away from these pipes. If it is fixed as the slide suggests, circulation is apt to be set up in the boiler pipes.

The author also showed a calorifier fitted with a circulator; the only way in which we have been able to overcome the numerous difficulties of this type of installation is by employing an outside circulator with bosses fitted to the external cylinder.

As regards the complaints which are sometimes made about the plumbing work in connection with electric water heating, in numerous cases this can be traced to the manufacturers not standardizing their tappings for inlet and outlet connections.

In this district many copper cylinders are fixed having a total capacity of 20 gallons, and when a circulator is fitted these barely give 15 gallons of water at 150° F. Care should therefore be exercised when advising the installation of a circulator. Many people are under the impression that the system will heat water as quickly as it is drawn off.

Regarding hotel installations, many of these have secondary circulations and are therefore not suitable for electric water heating. I think the only method of overcoming this difficulty would be to fit a pressure release valve to the secondary flow and have this wired so as to keep the temperature below the pressure setting on the valve. An extra circulator could be fitted and brought into use in the early morning, thereby lifting the valve and allowing the installation to work normally.

I have been asked on numerous occasions " Why is our consumption so heavy?" In quite a few cases excessive consumption is caused by reversed circulation, the cylinder in which the circulator is fixed becoming the boiler, and the boiler already in the fireplace becoming a cylinder. This often occurs in flats and bungalows and is caused by the plumbing installation being somewhat out of the ordinary. In such instances I would advise a check-up of the system before passing any comments on consumption figures. The only effective way to cure this trouble is by fixing a vertical non-return valve to the flow pipe from the boiler, at a point adjacent to this.

Mr. J. Eden: There are always three primary considerations to be settled before it can be claimed that the electrical water-heating system will be completely satisfactory, and they are (1) the effects that extensive development will have on the supplier, (2) the design of the installation, and (3) the cost to the user. The supplier has to consider the all-important question of diversity, because it is on this question only that a decision to proceed with large-scale development depends. Conditions will vary for each individual district, and in contrast are two districts—one comprising a London suburb and the other a typical mid-Tyne district. In one the demand is that of a dormitory area, whereas in the other conditions are representative of a normal industrial area, in consequence of which there is likely to be a large demand created in the middle of the day because a large proportion of the workers go home at approximately the same time for a midday meal. The problem is one for each local supply authority, but I know that some have reduced their difficulties by installing heaters with a total loading less than that suggested in the latest E.D.A. recommendations, with the result that the load is spread over a longer period.

The running cost, generally, will be the first consideration of the user, and by the creation of special tariffs for this service it is not difficult to make out a sound case for electric water heating. But equally important with the establishment of a low cost is the ability to decide accurately the requirements of the user, to provide the most satisfactory arrangement, and to educate the user with respect to its use. In this connection, the author indicates that one of the most extensively used heaters is the 1½-gallon displacement type fitted immediately above the kitchen sink. I appreciate that this type is preferred in this position probably because the first cost is low, but I feel that the first cost for the provision of an expansion pipe fitted to a pressure-type heater would soon be recovered through the saving that would be possible on account of the absence of the loss after each shut-off, due to the action of the siphon in the displacement-type heater.

On page 1 it is suggested that in soft-water districts copper containers should be used, whereas it would be quite satisfactory to provide iron tanks in the hard-water districts. There can be no general rule based on the hardness factor of the water, and it is interesting to record that, in contradiction of the author's suggestion, in a hard-water district over a period of 5 to 15 years more than 250 iron tanks corroded and had to be replaced; whereas in a comparatively soft-water district similar iron tanks installed at the same time are still giving satisfactory service.

Nor can there be any general rule in regard to the temperature at which an electric heater can operate in a hard-water district, for once a temperature has been reached when scaling will commence, although the rate of precipitation may be low it will be progressive. In this connection it is interesting to record that in a hard-water district in the Ipswich area the precipitation is 25 % at 120° F. and 50 % at 140° F., and at Reading the deposit is 11 % at 120° F. and 33 % at 140° F. The main problem is the form the deposit will assume; in this particular district we have to contend with a very solid, hard lime deposit which is difficult to remove, whereas in the Reading area the scale is of eggshell thickness and is due to the action of free chlorides.

I mention this latter point because the author states that chlorination tends to reduce the amount of scale. Unfortunately, however, the scale which is produced is one of the worst types it is possible to produce on an electric immersion heater, or, for that matter, on any container which is transmitting heat from the inside to water surrounding it. I feel that it is not so much a question of providing anti-scale devices as of preventing adhesion of the scale to the surface of the container tube, and I should like to ask the author whether he is aware of any means of achieving this result without the addition of salts or chemicals which could not be permitted in domestic systems. For my part, I have recently been associated with an investigation which has provided every indication that it is not impossible to prevent a particularly difficult type of scale from adhering, and I am very hopeful that the scheme will be commercially practicable.

On page 3 it is suggested that the necessity for tinning is a debatable point. Tinning initially was intended to prevent the contamination of the water, but I think that experience has proved that the tinning serves also another very valuable purpose, for as long as the tinning is sound there will be no corrosion of the copper, which would be possible otherwise owing to the presence of active chemicals in the deposit. I therefore feel that it is still imperative that the copper components in the domestic electric water heaters should be "dip" tinned in accordance with the original requirements.

I am at a loss to appreciate the value of Fig. 3, from which it is possible to obtain one efficiency value for a $1\frac{1}{2}$-gallon water heater of 99 %, which is improbable. I suggest that the whole question of efficiency is bound up with the type of system to which the heater is connected.

I cannot attach any useful value to the curves shown in Fig. 9, because the conditions determining the efficiency will be constantly varying and the true heat-loss curve at any time will be asymptotic to the curve of room temperature and can be represented by the condition

$$\log_e \frac{\tau - \tau_2}{\tau_1 - \tau_2} = -Kt$$

where K is the ratio of the heat content to the cooling surface, τ_2 is the room temperature, τ_1 the initial water temperature, and τ the water temperature after time t. The same relationship exists between the heating element and the water heater, but in this case the factor K will vary considerably with the scale.

I suggest that there are simpler (and equally effective) arrangements for controlling the supply to domestic electric water heaters than the remote control system mentioned by the author; one satisfactory system that has provided the desired result uses a relay installed on the consumer's premises to record the total lighting and power load connected at any instant and to disconnect automatically the water-heating load when the sum total of all the other loads has reached a predetermined value. The arrangement has the advantage that the additional capital cost is small and the individual requirements of each consumer can be taken into consideration so that the greatest possible benefit can be ensured to the supplier.

The author does not mention a market which, I feel, has great possibilities, and that is the provision of hot-water services in hotels, boarding houses, and the like. At the present time many of the owners of these premises are having to consider the addition of a hot-water service, and because of the rambling nature of some of the property the best results can be obtained by having the heater at the point where the hot water is required. Very satisfactory results have been obtained with a wash-basin which embodies a storage heater below the basin in a pedestal. Installation costs are low, since only a cold-water feed requires to be brought to each wash-basin.

Mr. N. T. Smith: I am sorry that the author does not deal more fully with the belt type of heater. I find that the average self-contained heater is too expensive in installation for the average consumer, who is more interested in conversion systems. In the hard-water districts the belt type of heater, with its easy fixing and removal, no special plumbing, and no corrosion, offers many advantages over the immersion type. The efficiency is comparable with that of the immersion type, and as the belt has a larger area of heating contact with a low heat density a higher loading with quicker heating may be adopted.

My experience of the sheath-type withdrawable element is that, owing to continual flexing, it is sometimes impossible to withdraw the element.

I have found that in the hard-water districts scale forms at a temperature as low as 130° F., and I would suggest that the cold-water baffle in self-contained heaters should be fixed as close as possible to the element, as the chilling effect tends to cause descaling.

I have found the consumption of the cistern type of water heater to be unduly high in comparison with that of the semi-pressure type, possibly owing to insufficient lagging between the tank and the heater, and I should be interested to know the author's experience in this direction. I consider that lagging is absolutely essential in every installation where electricity is to be used for water heating.

A criticism I sometimes have to offer of water heaters is that the elements are not withdrawable without disturbing the water connections; maintenance costs would be reduced if manufacturers would pay attention to this point.

[The author's reply to this discussion will be found on page 50.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 6TH FEBRUARY, 1939

Mr. A. Manighetti: I am surprised to find that the author makes no mention of porcelain and glass water containers, as Continental practice is swinging over to the use of these. One cannot fail to be attracted to the use of such materials as glass or porcelain, which are 100 % hygienic, for the manufacture of hot-water containers used for drinking and culinary purposes. Moreover, a glass container is everlasting, very easily cleaned, and quite free from corrosion by any type of water. It has been suggested that there are constructional difficulties associated with the use of glass, e.g. the making of an effective glass-to-metal joint. One manufacturer in this country has produced a unit embodying a Pyrex-glass interior, and after investigation of this I feel satisfied that a sound and efficient seal can be designed. It may be of interest to explain the method. The rim of the container has a ground surface, and on this rim a Dermatine washer of U section is tightly fitted. Clamps of special design, which ensure the application of even pressure, secure the container to the base ring, and the baseplate is secured to the ring by studs in the usual manner.

The flow pipe, the most vulnerable part as regards fur deposit, is detachable, and also made of glass. It appears that in this design a considerable reduction is obtained in the area of metal liable to scaling, and I should appreciate the author's views on heaters of this type.

Captain J. Coxon: On page 12 the author refers to the necessity of preventing heat losses via the expansion pipe, and suggests a heat trap formed by using a horizontal pipe at the top of the cylinder not less than 1 ft. long. In practice I find that this arrangement is not satisfactory. With a $\frac{3}{4}$-in. copper pipe the hot water continues to circulate up the expansion pipe to the water level. Should not the pipe be dipped instead of being horizontal?

Secondly, the author suggests for quick heating the addition of a second heating element, hand-controlled by a separate switch; I feel that this arrangement would not be satisfactory in practice, as the second element is liable to be left "on," resulting in excessive consumption and, possibly, boiling. If a second element is provided it should also be thermostatically controlled.

Thirdly, Fig. 11 shows a domestic fuel boiler and circulator working in conjunction with electric water heaters, the feed to the latter being taken from the expansion pipe of the circulator. With this arrangement there appears a risk—if no water is being drawn off—that the water in the electric heaters will cool and the thermostats close the circuits, although there may be ample hot water in the fuel boiler and circulator. Can the author suggest how this loss may be avoided?

Prof. W. Cramp: In Fig. 3 the author shows an important relationship, which, however, is incomplete on account of the absence of the ambient temperature upon which the curve must depend. I hope that he will give this in his reply. He favours almost exclusively the adoption of granulated cork as lagging for domestic tanks. He even advises its use around rectangular tanks in wooden drying cupboards. I disagree, because such cork is dusty, is apt to form a breeding place for insects, prone to solidification where any vibration exists, and exceedingly inconvenient when any repair to the tank is needed. Cushions containing slag wool or asbestos flock are cleaner and more easily removed; but better still is the use of sheets of crinkled metal foil, which are cheap, light, clean, and very easy to install. For a given lagging space they will bear comparison with any other system. For granulated cork 3 in. thick the author gives a loss of 4 watts per sq. ft. for a temperature-difference of 60 deg. F. The corresponding figure for the same thickness of crinkled foil, deduced from the N.P.L. tests on "Alfol," is just over 3 watts per sq. ft., and the cost of the material is only about $6\frac{1}{2}$d. per sq. ft.

Again, too little stress is laid upon the importance of pipe losses, especially in old houses, where often the hot tank is a long way from the taps and constructional alterations would be very expensive. In one instance, I found that lagging such pipes increased the maximum temperature attainable from a coal-fired system by no less than 20 deg. F.

Finally, the author barely mentions the use of an electric circulator external to the tank, which often is more convenient than an immersion heater. Would he kindly give his opinion of this arrangement?

Mr. E. T. F. Onley: I have noticed that in many of the houses which are now being built the hot-water tank is placed in the corner formed by two adjacent walls of the bathroom, thus making it practically impossible to place an effective lagging on these two sides of the tank should the purchaser later on decide to fit an immersion heater. I have suggested to several builders the desirability of so placing the tank and, if necessary, slightly increasing the dimensions of the airing cupboard, that there is a space of about 2 in. at the top and bottom and around the four sides of the tank to allow room for fitting an efficient form of lagging; and I am glad to say the suggestion has generally been well received.

I would also suggest that it would be an advantage if the builders could be educated to lag the pipes from the tank to the hot-water taps, because with the normal intermittent use the hot water left in the pipe represents a heat loss which is a fairly large percentage compared with the heat content of the water drawn off for use.

With regard to the question of thermostatic control versus hand control, I favour a combination of the two, especially for an immersion heater which is being fitted to an existing domestic hot-water system, where it is sometimes difficult to fit highly efficient lagging without slight structural alterations, the cost or nuisance of which may prove a deciding factor militating against the installation of an immersion heater. In my own home I found that by switching the heater off overnight the average daily consumption (three in family) was reduced from 15·5 to 12 units, which at 0·5d. per unit represents an annual saving of £2 12s.

Mr. J. M. Hollander: My own view is that the question of providing a cheap and abundant supply of hot water for houses is by no means solved, and I am not satisfied that concentrating on relatively small storage heaters or installing immersion heaters in tanks is what is required. I am sorry to note that the electric geyser is condemned in the paper, and I should like to have a little further information on this subject. I understand that electric geysers have been rejected by several supply authorities, more on the grounds of peak-load problems than in consequence of any inherent defects.

As regards the difficulty of waste due to the delinquencies of the domestic staff when hand control is installed, I get over this by putting in a 2-way control, one switch in the bathroom and the other in the scullery, with pilot lights.

So far as the general question of the water-heating load is concerned I feel that the supply undertakings have made the best of a bad job. They want to encourage the water-heating load, yet they are rather afraid to do so in a wholehearted manner because of what it might mean to their maximum demand. Possibly the more general adoption of 3-phase supplies to domestic premises might help considerably. If, instead of a single immersion heater or circulator of a rating up to 3 kW, three such heaters were installed, connected between each phase and neutral, the recovery period between successive draw-offs of considerable quantities of hot water would be so reduced as to make all-electric water heating a convenient and economic proposition.

Mr. W. Rendell-Baker: In 1932 the company I am associated with started to study this problem of how to give an ordinary householder a constant supply of hot water at a price he could afford to pay—something which he had never had before. The major portion of our area is served with hard water, and so we designed an apparatus plate which would keep the element well away from the thermostat, thus keeping the maintenance costs down. We also noted that many thousands of our consumers obtained their hot water from the back-boiler, which was not available in the summer; so we concentrated on that type of installation. We were able to meet normal requirements using 1-kW loading and a suitable apparatus plate that can be bolted on to the side or the top of the hot-water tank, with an adaptor which can be made to fit either a round or a rectangular tank, and to take one or two elements according to the load. The thermostat is set down to 150° F., and the conversion costs the company about £5. The cost to the consumer, averaged over 750 installations, is 1 590 units per annum, or 1s. 8d. per week. For this we give constant hot water at all taps. We have installed several thousands of these units since 1932, and, apart from the cost of attention to sticking thermostats, we have had no maintenance charges. The demand is increasing as the public gets to know that this service is available, and we find that we can sell about six installations of this type to one self-contained heater. The only difficulty which may be met with is that of circulation in the pipes. When there is any doubt as to whether the immersion heater is functioning properly, a recording voltmeter should be connected across the elements, and on examining the chart one can tell quickly and definitely whether circulation is taking place. If it is, the thermostat will operate every 2 hours during the night, whereas it should only operate every 5 or 6 hours.

Mr. J. H. Fella: I would draw attention to the recently-issued B.S.S. No. 816—1938, which stipulates that the temperature of terminals to which insulated cables may be connected should not exceed 170° F. Fig. 6B shows that with conventional circulators the temperature of the water at the top may rise to over 200° F. with a normal thermostat setting. As the terminal temperature will approximate to this figure, am I right in concluding that this type of apparatus does not comply with B.S.S. No. 816?

I am sorry to see that the author condemns two types of heater—the geyser and the self-contained automatic immersion heater. He remarks that a 4-kW geyser would be useless for heating a bath; but so would a 1½-gallon storage heater. Would not a 4-kW geyser have useful application in the same situations as the 1½-gallon storage heater? From the supply authorities' point of view the geyser is not so desirable because of its larger loading, but it offers an attractive selling point in that there are no standing losses, and the quantity of water given would not be unreasonable for wash-basin or kitchen use.

With reference to thermostatic control of immersion heaters, the author states that "more certain action is usually obtained if the thermostat is fitted some distance —6 in. or more—away. . . ." I am not quite clear what he means by "more certain action." I have tested self-contained heaters of the tubular sheathed-wire type having a thermostat mounted between the elements, allowing free water circulation round it, and on the basis of these tests the cut-out temperature appears to differ very little from that obtained by mounting the thermostat 6 in. away. I would suggest that this small difference is of little importance compared with the lower cost, smaller installation, and more convenient arrangement offered by the self-contained heater.

Mr. J. A. C. King: Has the possibility of using something on the lines of the electrode boiler been considered for domestic water-heating where there is hard water? The electrode boiler needs a certain amount of salt in solution to make it function.

I do not see any mention in the paper of external circulators for attaching to existing installations. I have come across calorifiers which, instead of having a coil to contain the water from the primary heater, use a cylinder whose capacity may be half that of the main cylinder. It would be difficult to fit an internal circulator to such a calorifier, and the only solution would be an external circulator.

Turning to the subject of tariff reductions for water heating done at night, I suggest that, especially in new houses, a slightly larger tank might be installed with fairly heavily loaded elements set to raise the water temperature to something very close to boiling point during the night. In addition, a small heater might be provided for use if extra hot water is required during the day. This would be controlled by a manually-operated switch and a thermostat. The simple hand control seems to be a danger in that someone might forget to turn it off, and then one would get steam instead of hot water.

One of the author's slides showed two vertical boilers with what looked like a series of large bladed-type immersion heaters near the bottom, but stepped round the boiler. I should like to ask whether the idea of these is to cut off the consumption gradually, or just to avoid the blades clashing with each other inside.

I should like to know what type of thermostat the author favours. There seem to be two general types—one in which a rod is enclosed within a tube made of a different metal and it is the difference in the linear coefficient of expansion which operates the thermostat, and the other where a bimetallic strip is used which bends to make and break contact. I should like to know whether the latter is found successful, or whether the rod-and-tube type is used exclusively for water heaters.

It has been suggested that where supply has to be given to a number of large blocks of flats, preferably near an attended substation, all the water-heating appliances should be connected to special distributors, the voltage on which would be lowered by the substation attendant during peak-load periods. In this way the current would be reduced, since most of the water-heating is done by some device with a constant ohmic load.

Mr. R. H. Rawll: I agree with the author that in developing the water-heating load it is most essential that supply undertakings should have on their staffs men whose sole job it is to do this work. As the author has shown, there are many cases where water heating may provide difficulties if electricity is applied to it, and there is nothing worse from a selling and propaganda point of view than to find subsequently that the installation is unsuccessful. It is far better to inform the consumer in the first instance that one cannot make a satisfactory job than to provide a very inefficient and uneconomical installation.

Statistics show that whereas in the South of England storage heaters seem to be the more popular, in the North and the Midlands the preference is mainly for circulators. This preference presumably depends not only on the degree of hardness of the water but also on the habits of the people. The author mentions that in districts where the water is comparatively soft the thermostat of a 1½-gallon storage heater may be set at 190° F. and that as the hardness increases one may have to reduce this to about 150° F. We have comparatively soft water in Birmingham, but we have found it necessary to set our thermostats at about 160° F., primarily from considerations of actual consumption; there seems to be an optimum figure for thermostat settings, and if the setting is increased beyond this a pronounced increase in consumption will often result.

The figure of ¾ unit has been given as the average 24-hour stand-by loss in a 1½-gallon storage heater, and this raises a rather interesting point. We found in Birmingham that a certain number of consumers were in the habit of switching off these small storage heaters at night and switching them on again in the morning, thinking that they would thereby save current. Actually, the reverse is the case; consumption tests show that it is more economical to leave the heater on during the night. The question of supplying hot water to flats is a very thorny problem. In my experience it is essential to make the approach in the early days when the architect is designing the building, because unless the heater is made to measure it probably will be impossible to install it; and even if it is made to measure it is often difficult to fit it in position, especially in working-class flats.

I understand that some supply undertakings have had unfortunate experiences with automatic lagged systems. In one case where an undertaking started a scheme for hiring out water heaters fitted with thermostatic control the consumptions were so high that many of the installations had to be removed. The people concerned had not had constant hot-water service before, and they were not prepared to pay for this convenience. We therefore only hire water heaters with hand control, but if people wish to have thermostatic control this can be provided if they pay for it by cash or on credit sale terms.

Mention has been made of the necessity of observing whether one of the circulating pipes on an installation feeds a sink tap, since in such circumstances, if a circulator is fitted in the tank, it is essential to transfer the tap to the hot-water feed pipe to the other taps. There is another point in this connection which has to be watched. Where there is a hot-water towel rail in the bathroom we always tell the consumer that before a circulator can be installed a stop-cock must be fitted to the towel rail to avoid circulation round it.

I am not in agreement with the author that for economical reasons 15 ft. is the maximum distance which a sink tap should be away from the central tank in which a circulator is connected, and that after that length has been exceeded a small storage heater should be fitted at the sink. It seems to me that this question rather depends on whether the tank upstairs is thermostatically operated or not. I think the author intended to imply that the tank upstairs is thermostatically controlled, because if hand control is utilized in all probability the water may not be used downstairs at the sink tap throughout the day. If, on the other hand, the tank is thermostatically controlled, hot water will be drawn from the sink tap and in such circumstances a considerable loss will naturally be experienced.

I am interested in the author's curves showing consumptions in various types of flats. In a block of flats or a housing estate of the ordinary class, two families of the same size with practically the same salary and (as far as one can ascertain) the same external habits usually have very different habits from the point of view of the use of hot water, and thus it is very difficult to estimate the probable consumption in any given case.

The author states that a self-contained heater can be connected direct to a distribution fuse-board without a switch. We put in a double-pole switch near the storage heater, and we think this is very necessary for safety reasons, apart from complying with the I.E.E. Wiring Regulations.

Dealing with installation matters, we utilize asbestos-covered wire on our circulators between the terminal box of the circulator and a small joint-box which we fit inside the airing cupboard. I should like to have the benefit of the author's views on this matter. We feel that this practice is advisable because not only may there be a risk with regard to the perishing of the rubber of ordinary cable owing to the heat, but asbestos-covered wire gives a degree of confidence to the consumer, who possibly is in some doubt as to the safety of electricity in the bathroom. We think it is also very advisable to have this joint box fitted inside the airing cupboard, so that if the circulator has to be removed subsequently the asbestos wire is merely disconnected and one can then be satisfied that the wires to the airing cupboard will be quite safe even if the fuses later on are inserted.

As regards the diversity of the electric water-heating load, what we want is curves showing the actual diversity or varying demand on the distributing network itself for the whole of the domestic load, and not merely that due to water heating. It may be true that the low-loaded heater has a high load-factor and the high-loaded one gives a lower load-factor, but the supply authorities are mainly interested in the effect of the combination of all the other pieces of domestic apparatus on the network and it may easily happen that apparatus other than water heaters may be switched on when the latter are not in circuit, and therefore will tend to smooth out the general shape of the load curve. Most undertakings are to-day alive to this point and are endeavouring to obtain this information.

Should one restrict the supply to a domestic consumer? My own view and also that of my undertaking is that no restriction as regards the hours of use should be placed on a domestic consumer with respect to a particular piece of apparatus. I think that if there is going to be any restriction it should be applied before the particular apparatus is connected and should apply to the type of apparatus and not the hours of use. Our job is to provide electricity, and if we can only produce apparatus to work at certain times we have failed in our job.

Finally, I would say that the question of introducing electric water heating into houses falls into two distinct categories, namely conversions and new installations. As regards the conversion of an existing hot-water installation, it is a matter of making the best of the job, taking all the circumstances into account, and usually one must also do it at a comparatively low price. With respect to new houses, one must make contact with the builder in the early stages, because provided the electric hot-water installation is considered before the usual and older method involving a solid-fuel boiler is decided upon, the builder should realize a net saving on his total building costs.

[The author's reply to this discussion will be found on page 50.]

NORTH MIDLAND CENTRE, AT LEEDS, 14TH MARCH, 1939

Mr. D. H. S. Sanderson: I do not consider that there is any advantage in the withdrawable-pattern heating element. The object of the element is to convert the electrical energy into heat and then to get it into the water, and the designer's desire is to have as small a temperature gradient as possible between the resistor and the water. He must insulate the resistor electrically, and yet the insulating material must conduct the heat. The thicker the insulator, the greater the gradient. In order to make an element withdrawable the designer must provide an air-gap, which is a good insulator and a bad conductor. The main disadvantage of air, however, is that it oxidizes the resistor, and oxidation is, generally speaking, the cause of its failure. By embedding the resistor, oxidation is virtually eliminated, whilst the element can then comprise resistor, insulator, and sheath only, instead of resistor, insulator, air, and sheath.

Regarding watts densities, I have seen a batch of elements, all fitted in one tank, heating hard water, of varying densities from about 30 to over 80 watts per sq. in. There was little difference in appearance, and although there was a large quantity of scale deposited on the tank bottom, it was not possible to say whether it was the lightly loaded or the highly loaded heaters which were responsible. Sometimes a scale deposit $\frac{3}{8}$ in. thick is found on electric water heaters in hard-water districts.

In this part of the country we are generally blessed with soft water, and most houses have a fire-back boiler from which the water rises, when heated, to a copper cylinder. Unless legislation is brought in to prohibit the use of raw fuel in domestic grates the fire-back boiler will be used for many years and therefore electric heaters will be generally employed as boosters, serving as the sole source of heat only when the fire is not in use, as in summer.

An immersion heater or circulator is, in these cases, the most convenient and useful form of electrical heating. It is easily fixed, and gives hot water at all existing hot-water taps. The use of the circulating tube is an advantage in that it makes hotter water available during the first 10 or 15 minutes, but where a quantity of water is wanted in an hour or so, then there is little advantage providing the heater is fixed vertically or nearly so.

A 3-kW circulator meets most household requirements. It gives hot water in small quantities in a short time and it gives sufficient hot water for a good bath in $1\frac{1}{4}$–$1\frac{1}{2}$ hours. If the cylinder is large, say of 40 gallons capacity, and the requirements are rather heavy, I consider that the best method is to install two heaters—a circulator at the top for general use and a horizontal immersion heater at the bottom, that may be switched on when larger quantities of hot water are required.

As the cylinder is generally fixed in or near to the bathroom, I advise the use of a $1\frac{1}{2}$- or 3-gallon storage heater at the kitchen or scullery sink. These small storage heaters save pipe losses, are very efficient, and have a low loading—750 watts is the now recognized standard. Their recuperation period is rather long, but I do not think that for ordinary domestic purposes that matters a great deal. The author in Table 4 indicates that they may be used for making tea, but I do not think that the de-aerated water given by a storage heater would be suitable for this purpose or for boiling vegetables.

I should like to explain the working of the anti-scale device shown in Fig. 5A(*b*). When the heater is first installed and the water turned on, the heating chamber is filled, as well as the storage chamber. By an ingenious yet simple arrangement of a tube and a cap an air lock is formed which seals this charge of water round the heating element. The small amount of hardness in this initial charge is soon thrown out and the water surrounding the element is then soft. This water conducts the heat to the heater-chamber wall and thence to the main bulk of water. As the temperature of the wall does not exceed 160° F. practically no scale is formed, whilst the element itself is free from scale.

I examined a 3-gallon heater fitted with that device in an electricity showroom in one of the few hard-water districts (28 degrees of hardness) near Leeds, and found that after 11 months' hard use the tinned copper sheath was quite bright and the total amount of scale thrown down or accumulated on the heating chamber was only 2 oz. It was also noticed that the thickness of scale was very small—from 0·020 in. to 0·030 in.

Regarding the loading of the elements for storage heaters, I believe one or two supply authorities favour 2 000 watts on 1½-gallon heaters. Whilst I do not see much harm in this suggestion from the diversity-factor point of view, it will only be possible to adopt it in soft-water districts. If such a concentrated loading were employed in a hard-water district a lot of scale would be thrown down. The main disadvantage I foresee is that when people have been able to get a more or less instantaneous supply from a 1½-gallon storage heater they will demand considerably higher wattages in larger containers. What has been the experience of users of 2-kW 1½-gallon storage heaters with regard to boiling? The period of recuperation is presumably very small, and I do not know whether the thermostats will act quickly enough to prevent boiling.

I would stress the importance of making sure that there is an adequate expansion pipe on every installation and that it rises continuously to the feed tank, or, as the author shows, has only a short horizontal run. It must not drop, otherwise an air lock will be formed which can cause considerable trouble. I came across an instance where the expansion pipe rose from the cylinder and then came right down to the floor level. The hand-controlled non-automatic 4-kW heater was left on by mistake one night, an air lock was formed, and the water was pushed back some inches, by pressure through the feed pipe up into the cold-water feed, and the tops of the element blades were exposed. Being exposed in air the blades were not conducting the heat into the water, they became overheated in a relatively short time, and the soldering of the flange was melted. Leakage of the water commenced, and continued all night, causing considerable damage.

Mr. E. Hallowell: I should have liked the author to have devoted more space to the purely economic facts of electricity supply for water heating.

Many engineers will not subscribe to his statement (page 17) that water heating is the best of all domestic applications of electricity, though had he qualified the statement by saying "off-peak water heating" many would have been in complete agreement. The very high thermal losses incurred in converting heat into electrical energy at the power station and in transmission to the consumer's premises militate against the use of electricity for heating purposes, but these losses—large as they are—become comparatively unimportant when one considers the high capital charges for equipment and mains which are incurred in giving supplies to small consumers. If reference is made to published figures it will be seen that where domestic supplies predominate the total capital cost per kilowatt of maximum demand on the system as a whole often reaches the sum of £100. If interest, depreciation, and maintenance are taken at the low figure of 7 % one arrives at a cost of £7 per annum per kW of maximum demand, to which must be added central-station or C.E.B. demand charges, making a total of at least £10 per annum per kW of maximum demand.

Taking the author's own figures (Table 8), a 2-kW water heater using 3 750 units per annum will create a maximum demand of 0·95 kW after allowing for diversity, which, on the above basis, works out at 0·6d. per unit for capital charges only. To this must be added a basic charge of, say, 0·15d. per unit to cover coal and rates, making a total cost to the supply undertaker of ¾d. per unit at the consumers' terminals. If one accepts the author's figures, which incidentally agree with my own experience, the position in regard to circulators is even worse, particularly when early morning peak-load conditions exist. It is apparent, therefore, that a domestic rate of 0·5d. per unit is quite unprofitable when the supply is unrestricted, and supplies at present given on this basis must necessarily be subsidized by power and lighting consumers. With controlled supplies the position is quite different. Capital charges amounting to upwards of 80 % of the total cost are completely eliminated, and water-heating tariffs as low as 0·25d. per unit become remunerative.

The fundamental objection to all forms of off-peak control is the need for adequate thermal storage, to bridge long peak-load periods, and any successful method of control must aim at reducing this thermal storage to a minimum. So-called load-levelling of cooker and water-heating loads can have little beneficial effect in reducing maximum demand, since an increase in load factor is usually accompanied by a reduction in diversity factor. Also long restriction periods become necessary if water heaters are disconnected whenever cookers are in use. Time switching is also difficult to apply successfully, owing to the difficulty of predicting the times of peak load.

The company with which I am associated has installed a ripple control system which successfully overcomes these difficulties, so that the thermal storage provided by an ordinary converted domestic cylinder is found to be quite adequate to meet all normal demands. Under this system, instead of the whole load being disconnected and reconnected some time before and after each peak, it is automatically controlled step by step to follow the contour of the load curve, which in itself approximately halves the restriction period. Furthermore, water heaters are disconnected and reconnected in an order determined by the temperature. Thus the consumers who most urgently require supply take precedence. For example, those who require supply after a period of heavy demand for hot water will be disconnected for not more than 30 minutes, whilst those having a supply of water at a reasonably high temperature may be off for longer periods up to, say, 4 hours. In effect the system takes advantage of diversity in demands for hot water, and there is a minimum of inconvenience to the consumer with a maximum load factor for the supply undertaking.

Mr. S. F. Osborne: The paper covers only the general principles of domestic water heating. It would have been of much greater value to supply engineers if it had given more details of recent improvements in the design of apparatus, comparisons of operating characteristics of different types of immersion heaters and circulators, the effect of various thermostat positions and lengths, and other points which require special consideration.

The estimated load characteristics given in Table 8 do not serve any useful purpose. Similar estimates of load and diversity factors have been published by eight different authorities in various technical journals during the past 2 years, but these figures differ widely, and those given by the author do not compare with any of them. At the present time, one cannot do more than give rough estimates of diversity factor, but supply undertakings installing "off-peak" control apparatus operating by superimposed high-frequency currents will be able to determine exactly the diversity of the apparatus at any time of the day by recording the fall in load at a distribution centre or substation when a control signal is sent out and water heaters are disconnected. With such information it will be possible to determine exactly the costs of supplying the domestic water-heating load.

There is not much difficulty in the North Midland areas with regard to hard water, though there are a few water authorities supplying water with over 30 degrees of temporary hardness. Difficulty is experienced in one area where the water authority obtains its supply from two different sources, one providing very soft water and the other water with 28 degrees of temporary hardness. When it is not possible to obtain particulars of the area supplied by each source, apparatus suitable for hard-water supplies must be used throughout the area.

With regard to the allowance made in designing solid-fuel domestic hot-water installations, statistics recently obtained by the inspection of about 3 000 houses and information given by the manufacturers of domestic hot-water cylinders, show that the size of storage tank installed in 5-, 6-, and 7-room houses varies from 15 gallons to 50 gallons, the average size being 21 gallons.

Reference is made to the state of development in certain towns in the South of England; 25 % of the consumers in certain towns are said to be using electricity for water heating. Several undertakings in the North have obtained equal results. The reason for the high percentage of consumers using electricity for water heating in Switzerland is partly the lower cost of electricity and the comparatively high cost of coal.

Several undertakings are hiring belt-type heaters and external circulators. These do not appear to be very popular, but no trouble has yet been experienced by the undertakings installing them. Belt-type heaters are particularly satisfactory for hire schemes, as no tank drilling is necessary and the apparatus is easily recovered. The belt heater has, however, a lower efficiency than the immersion heater.

I should like to know the source of the figures given in Table 2. Though it is necessary for undertakings to give the number of water heaters connected when completing the Electricity Commissioners' annual returns, many undertakings do not know how many water heaters are connected to their mains.

In connection with the design of the water container, there are reasons for tinning the inner container by the "hot dipping" process other than for the prevention of contamination of the water due to the absorption of copper which sometimes occurs when the water stands in the container for long periods; and it is unlikely that this process of tinning will be discontinued.

It has in the past been considered that low loading density of heating elements is necessary to reduce the element surface temperature, particularly in hard-water districts. It has also been stated that higher surface temperature and quick heating and cooling, causing rapid expansion and contraction of the elements, tends to throw off the scale. I understand that recent tests disprove this latter theory, and I should be pleased if the author could give any information on the point. There are several heaters on the market with special anti-scaling devices, but the author gives very little information on this type of apparatus. On page 4 he suggests that thermostat settings should be limited to 150°–160° F. where the water is very hard. It has been found in certain districts that, with thermostats set as low as 130° F., the rate of scaling has not been materially reduced.

Referring to Fig. 3, the ambient temperature at which the tests were taken should be given. The curve shows that for $1\frac{1}{2}$-in. thick lagging (which is standardized by several manufacturers) the weekly loss due to radiation is 2 units (0·3 unit per 24 hours), assuming that the water is maintained at 170° F. throughout the day.

Has the author had any experience with water heaters in which the ball valve is incorporated in the hot-water chamber? With this type of heater, the cold water is fed into the cylinder at the bottom, and hot water is drawn off from the top of the cylinder through a pipe connection to the ball float.

Referring to cistern-type heaters, the author states that the pressure is limited to the head of water between the bottom of the container and the top of the water in the ball-valve tank. This is incorrect. The head of water is limited to the distance between the top of the water in the ball-valve tank and the top of the water in the hot chamber—a head of about 6 in., compared with 4–5 ft. for the conditions given by the author. With a head of 4 ft. 6 in., the $\frac{1}{2}$-in. diameter feed pipe would be large enough to supply water at the rate of 9 gallons per minute (allowing for normal pipe and pipe-fittings friction losses). With a head of 6 in., the rate of flow for a $\frac{1}{2}$-in. diameter pipe would be below 3 gallons per minute. A feed pipe based on the author's assumptions would therefore be of too small a diameter to meet normal requirements.

The section of the paper dealing with immersion heaters and circulators refers mainly to top-entry type circulators, though the side-entry circulators give many advantages. For example, it will be seen from Fig. B, which shows the heating characteristics of a 2-kW side-entry circulator, that water is available in small quantities at the top of the cylinder at a temperature of 120° F. within 10 minutes of switching on. Compared with this, the curves given by the author in Fig. 6B show that it takes 20 minutes with a 2·5-kW top-entry circulator to obtain water at 120° F. The side-entry circulator can be installed close to the bottom of the cylinder. The full contents of the tank can therefore be heated. This is important where supplies of electricity are given on an "off-peak" tariff, and the maximum amount of heat storage is required. The length of circulating tube on the side-entry immersion heaters can easily be adjusted to suit various types of cylinders.

The main disadvantage of a side-entry circulator is that more room is required for the withdrawal of the element or thermostat in the event of a fault. It is often necessary to cut away the door or side of a small airing-cupboard to make provision for the apparatus terminal cover.

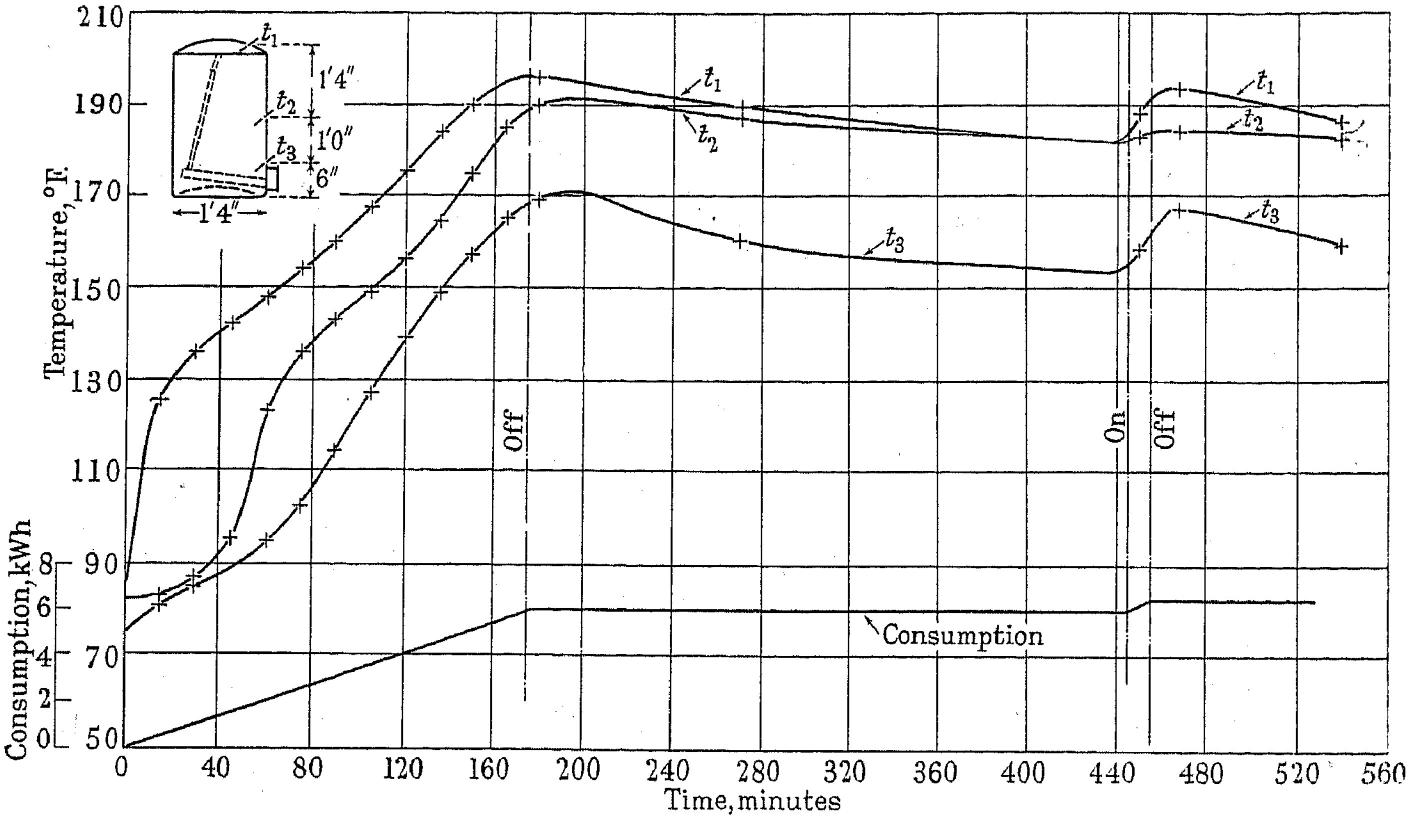

Fig. B.—Initial heating characteristics of 18-gallon copper-cylinder water heater fitted with 2-kW side-entry circulator with 2 ft. 6 in. long circulating tube. Thermostat set at 175° F.

With regard to the lagging of existing cylinders, the main difficulty with granulated cork lagging is that this must be removed to enable the heater to be withdrawn. Wool or asbestos insulating jackets are usually more satisfactory from this point of view.

The author mentions that safety from bursting of the storage cylinder is ensured by the provision of what he incorrectly terms an expansion pipe. Without this pipe, expansion would still be taken care of by the water travelling back through the open inlet to the heater. The main reason for the provision of the open outlet from the top of the tank is to release air which may be accumulated at the top of the cylinder and cause air locks.

With regard to pipe losses, one cannot lay down a definite rule as to the length of pipe to the kitchen sink beyond which it would pay to install a second heater. The diameter of the pipe and the frequency of use are additional points which need consideration.

I should like to point out that the revenue per unit of expenditure on water-heating apparatus in consumers' premises is greater than that for any other domestic supply. A 2-kW thermostatically controlled side-entry circulator can be installed complete with insulating jacket and 30 ft. of wiring for approximately £6. From this, the supply undertaking may obtain as much as 3 times the revenue which they would obtain from a cooker installation costing from £10 to £12, without having to provide for a maximum installed load of 6–7 kW, and without the danger of the high maximum-demand charges which are experienced during cold spells owing to the extensive use of electric radiators.

Mr. R. M. Longman: If one were to ask a domestic consumer who was accustomed to water heating by electricity which of the various electric services he would like to keep most, it is most likely that he would choose the water heating. My water-heating installation consists of a 2-kW immersion heater with 3-heat switch. It is placed horizontally about one-third the way up a 25-gallon cylinder, thus avoiding the corrugations. It is generally left on "low" all night and most of the day, and there is ample hot water for use the first thing in the morning. Probably 80 % to 90 % of the water heating is done at "low." There is no thermostat, as when the heater was installed 16 years ago thermostats were not so reliable as they are to-day.

It is of little use to employ electric cooking unless water heating is also provided and thus the open fire can be dispensed with during the summer time. The summer load is a great help to the undertakers, and improves the load factor. A disadvantage of a 3-kW heater is that it cannot be left on low (0·75 kW) all night unless it is controlled by a thermostat on an average-size cylinder.

The run of the hot-water piping really decides whether more than one heater or cylinder is needed. The run should be carefully examined to ascertain that the pipes are not exposed to draughts, and all holes for waste pipes should be properly filled in.

Encouragement of water heating at night would be a great help to the generating stations, particularly now that 30-MW and 50-MW sets are becoming so common. More night load is wanted, to avoid the necessity of shutting these plants down every night.

Mr. W. Dundas: It may be of interest to record my observations on the metering of the various services in a medium-sized house, where it was found that the water heater accounted for approximately 2 000 units per annum, averaging from 10 units a day in summer to 2 or 3 a day in winter, when the fire-back boiler supplies most of the hot water. The immersion heater is fitted with thermostatic control set to 150° F. on half its capacity, the remaining half being used as a boost to meet increased demands for hot water when necessary; this arrangement has proved to be exceedingly useful and flexible. Unfortunately, the water side was not metered, but the figure works out at an average of 30 gallons a day, which may be on the high side owing to the difficulty of estimating accurately the radiation losses on a boxed-in unlagged cylinder.

The electric water heater is such a boon to the housewife, reducing labour by the elimination of the kitchen fire, particularly in the summer, that the domestic rate offered in most places nowadays is sufficient to make the scheme attractive to the consumer. The domestic water-heating load, with its good diversity factor, is attractive also to supply authorities, especially under the conditions referred to above, and there should be no difficulty in obtaining custom at a rate satisfactory to both parties.

The conditions associated with off-peak load—increased capital commitments for storage, special switching arrangements, etc., together with the attendant inconveniences—are not attractive, and it is an open question whether off-peak water heating would be acceptable generally in a country such as ours, where alternative methods of heating are available and well established.

Mr. J. G. Craven: The great advantage of the system where the immersion heater is installed in the ordinary hot-water cylinder is that in the summer months and the late spring and early autumn one can have a bath by turning the heater on for 20 minutes or so after the kitchen fire has gone out in the afternoon.

Thermostats, now practically perfect in operation, have from the outset always been very reliable. In view of the number of thermostats that are in use to-day, it is remarkable how few failures there are, especially when one considers what a small break thermostat switches have, and what a large current they have to break when they are controlling 2- or 3-kW immersion heaters.

Does the author find that rectangular iron tanks are used almost universally in the South of England?

He showed a slide illustrating a cylinder lagged by what looked rather like a sack. Is this designed to enclose a certain amount of air in addition to the asbestos or cork, the air being a good insulator? I have lagged my own hot-water cylinder with asbestos matting. The cylinder is in a cupboard, with an airing compartment immediately above it. Much to my amazement, I find the temperature of the cupboard is as high now as it was before the cylinder was lagged. When the cylinder is hot it slowly warms up the cupboard, as there is practically no leakage of warm or hot air. Where the pipe comes up from the kitchen through the floor there is a large hole, through which dust is sucked up into the cupboard. Although the cylinder is lagged the connecting pipes are not, and they of course help to keep the cupboard warm.

There is no doubt that the use of electric water heating will extend in the future. A cheap form of control, with automatic switching, is essential, so that the energy can be supplied at a low price during off-peak hours.

Mr. C. W. Chandler: Referring to Fig. 5A, I have noticed that above the inlet pipe a baffle is fixed to prevent the cold water mixing with the hot water, and that a non-return device is not shown. Non-return devices which depend for their operation on the direction of flow of the inlet water actuating a ball or clack valve are not approved by most water supply authorities, and a much more satisfactory device in the form of an inverted U-tube having a small hole bored in the top of the bend effectively prevents mixing, and also acts as a non-return device.

According to the author, electric water heating is uneconomical if pipe-runs of 15 ft. or over are used between heater and tap. He states that the pipe loss is 2 kWh per day with 10 draw-offs if the water is drawn through 15 ft. of $\frac{3}{4}$-in. iron pipe, and if the water left in the pipe gives up all its heat after each draw-off; but he does not make a comparison with the figure of 1 kWh or more loss per day which occurs when hot water is stored in a $1\frac{1}{2}$-gallon thermal-storage heater. The thermal loss from a $1\frac{1}{2}$-gallon thermal-storage heater can easily amount to 180 or 200 kWh per half-year, which in many cases exceeds the combined house-lighting and radio consumption for a similar period.

Mr. Sanderson asked whether any trouble has been experienced by those authorities who adopt a loading of 2 kW in $1\frac{1}{2}$-gallon thermal-storage water heaters. In reply I would state that the authority for whom I work have adopted that loading as standard in both $1\frac{1}{2}$-gallon and 3-gallon water heaters, and so far no deleterious effects have become apparent. The thermostat operates quite efficiently and prevents boiling.

The reason why we have adopted this loading is our desire to meet the requirements of people residing in the poorer districts where both man and wife go out to work. When they return hot water is required quickly, and without the necessity for leaving the heater on all day. Moreover, we had to compete with gas water heating.

With a loading of 2 kW, a $1\frac{1}{2}$-gallon water heater having a thermostat setting of 170° F. has a preheating period of approximately 20 minutes, and for a 3-gallon heater the figure is approximately 35 minutes. The recuperation period depends on the quantity of water withdrawn, but if the full $1\frac{1}{2}$ gallons is used there is still the heat content of the inner container, and the time of recuperation is about 13 minutes. We are not troubled with hard water, so this relatively high loading can be used without fear of element failures.

I should like to mention that there is an anti-drip device on the market, working on the ejector principle, which makes use of a bell-shaped receptacle enclosing the inlet pipe. When the tap is opened the incoming water forces the water which is already in the bell into the main water chamber, so leaving an empty space into which water can run when the tap is turned off. This action reduces the level of the water below the top of the outlet pipe automatically and instantaneously, and avoids that undesirable but inherent feature of the siphonic arrangement—a flush of a pint or more of water in excess of actual requirements.

The author states that by arranging the heating elements to occupy the bottom third of the circulator length a better temperature-gradient is obtained than is possible with the more usual type where the elements are wound evenly throughout the circulator length. The graph in Fig. 6B shows that the temperature at the top of the cylinder after 10 minutes on circuit is about 95° F. for the circulator with elements disposed at the lower end, and about 115° F. for elements uniformly disposed. This small quantity of reasonably hot water is a feature that has made the circulator popular and that plumbers have striven for years to obtain. Plumbers have achieved some measure of success in this direction by connecting the return pipe from the fire-back boiler at a point nearer to the top of the cylinder. The normal arrangement of pipes is shown in Fig. 10, and it will be seen that the flow and return pipes for the fire-back boiler are within 6 in. of each other where they enter the cylinder.

With the standard type of circulator the top layer of water in the cylinder gets very hot, eventually boiling, and will probably rise 12 in. above the level of the water in the ball-feed cistern. Theoretically, a 24-ft. column of cold water will support a 25-ft. column of boiling water, but with turbulence increasing this disparity we have found in practice that hot water is forced out of the expansion pipe in increasing quantities until the air is completely expelled and a siphon formed by the bend of the expansion pipe, with the result that after a few minutes the hot water in the cylinder and the cold water in the ball-feed cistern have changed places.

The author's recommendation that 12 in. of horizontal pipe will reduce the temperature and consequent heat losses of the expansion pipe is not sound, and will probably cause water hammer. We have overcome the difficulty by fixing a small-bore tube just below the bend of the expansion pipe, the effect of which is to reduce turbulence and prevent water reaching the bend. Another effective and more simple method is to insert a small cylinder of about 1 quart capacity in the expansion pipe at a height slightly above the level of the water in the ball-feed cistern.

We in Bradford have dispensed with the circulator draught tube, with marked improvement, especially on narrow cylinders.

I am rather disappointed that the author makes no mention of the electric heating of the Rolyat-pattern combined cistern and storage tank. The Rolyat system employs a triangular tank, which serves the double purpose of a cold-feed ball-valve cistern and a hot-water storage cylinder. We have made several inquiries as to a satisfactory method of heating electrically tanks incorporating a copper coil, but up to the present we have not met with any degree of success. In the type not employing a coil we insert an immersion heater in the base of the tank and connected directly to the feed pipe supplying the hot-water taps. A pipe passes through the heater head and up to a point 1 in. above the element tubes, and the design is such that water is directed to it from the surface of the water by a float-supported tube, irrespective of the quantity of water in the tank. This arrangement is quite satisfactory.

The paper makes no mention of the 2-tank system found in old property, usually of 4–5 storys, where two tanks—often of 100 gallons' capacity each and connected together by a pipe and to the fire-back boiler—constitute the hot-water system. The trouble with this system is that the hot-water taps are fed from pipes taken from the riser from the fire-back boiler, and after a small quantity of hot water has been drawn, cold water rushes through the fire-back boiler and out at the " hot " tap. We have heated this system by divers methods, but generally by connecting a lagged cylinder in series with the riser close to the fire-back boiler, and installing an automatic circulator in the cylinder. The riser above the cylinder then feeds all taps and acts as the expansion pipe. A modification of this arrangement is to connect the cold-feed pipe to the cylinder and the fire-back boiler to the cylinder, so as to obtain a primary circulation in the cylinder.

Mr. J. W. Atkinson: I want to ask the author one question—whether many supply authorities provide immersion heaters on hire or whether it is the usual practice to supply them only on purchase or hire-purchase terms.

We are apt to get the impression that all the householders in this country now own their houses: this is quite a mistake, as there are millions of short-term tenants who cannot afford to undertake the purchase, or hire-purchase, of electric water heaters.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON, GLOUCESTER, MANCHESTER, BELFAST, NEWCASTLE, BIRMINGHAM, AND LEEDS

Mr. J. I. Bernard (*in reply*): The amount of discussion that the paper has aroused is no small tribute to the importance of this particular field of utilization of electricity and to the interest which is being taken in electric water heating at the present time. For the many contributions, which add so much useful knowledge to the information given in the paper, I should like to express my best thanks.

Space will not permit a detailed reply to every individual speaker and, as most of the minor questions were answered verbally, I hope the following general reply on the more important aspects will suffice.

General.

Dealing first with general comments, the remark of Mr. Butterfield that the subject is far from simple is quite true; it is only apparently simple and there are, as he says, some problems, such as designs for hard water and anti-drip devices, which are not yet completely solved.

Mr. C. H. Smith is right in emphasizing that the welfare of the whole of the electrical industry is wrapped up in the advance of the electric water-heating idea.

One of the most important practical advantages of electric water heating mentioned by several speakers is its very great reliability compared with other methods. Mr. McKenzie, for example, mentioned that even in the severe frost last December no defects were reported in 17 633 electric water heaters installed in Wimbledon. Another point mentioned by Mr. McKenzie—and one which is of importance to municipal supply undertakings—was that it is a matter of regret that the Electricity Commissioners recently granted an extension of loan period from 7 to 10 years for electric cookers but not for water heaters; such a distinction certainly seems anomalous to those who have had experience of the reliability of electric water heating.

A general comment should also be made on an aspect of the subject to which only slight reference was intentionally made in the paper, namely users' appreciation of electric water heating. As Messrs. Swale, Lennox, Dundas, Craven, Longman, and others testified, water heating is one of the most appreciated services that electricity can render in the household, and Mr. Taylor would no doubt find that the experimental conversion of his fuel-fired system, by fitting an immersion heater in a suitable manner, would not result in undue running cost.

Figures for the efficiency of other methods of water heating were not given, as they were thought to be rather outside the scope of the paper and such commercial considerations have been dealt with elsewhere.*

The title of the paper, which some speakers found misleading, does not, in my mind, bear the interpretation assumed; it is intended, of course, to cover the use of electric heating, by any method of application, for domestic hot water supply in commercial, industrial, or domestic premises.

Type of Water, and Use of Hot Water.

As Mr. Lennox pointed out, hard water is found in some districts north of the Trent where supplies are drawn from wells, such as South Shields, Sunderland, and West Hartlepool.

In reply to Mr. Grierson, the corrosive action of soft water is attributed to CO_2 as well as to acids, in several works of reference on water engineering (e.g. the "Water Engineers' Handbook").

In regard to the use of hot water, several speakers confirmed the wide variation which occurs as between different households. This lends weight to Mr. Parker's point that attempts should not be made to compute running costs to any considerable degree of accuracy for the purpose of furnishing consumers with estimates, as such figures may prove very misleading. As Mr. Ward pointed out, it is only after very considerable experience that a reliable estimate of consumption may be made.

I agree with Mr. Humphreys that the use of hot water is liable to be increased when electric heating is employed if an ample supply under thermostatic control is provided. On the other hand, a large proportion of weekly wage earners whose use of hot water is restricted by their means cannot be expected to pay for appreciable heat losses. The best type of electric water heater for this class of consumer is accordingly, as Mr. Millner points out, a subject for further study.

The discussions at Manchester, Leeds, and Newcastle indicate that the quantities of water for hand-basins and baths given in Table 1 are rather high for the North of England, but they probably represent conservative averages for the whole country. Generally speaking, existing hot-water systems judged on the number of gallons stored are of more ample design in the Midlands and South of England and Scotland than they are in Lancashire, Yorkshire, and other parts of England.

In reply to Mr. Rowson, the analysis of family incomes shown in Table 2 is estimated from the results of a number of surveys which, as he probably knows, vary considerably among themselves.

With regard to the number of water heaters in use, I agree with Mr. McKenzie that the ultimate criterion should be based upon the number of domestic premises rather than the number of consumers, but the former figures are not so readily obtainable.

The marked upward trend which occurred in 1936–37 in the number of water heaters connected, as shown in Figs. 1 and 2, is probably due to a combination of factors, including the more extensive availability of low costs of energy, but more particularly to the increased adoption of hire and hire-purchase terms by supply authorities; in reply to Mr. Chorlton, I am certainly of opinion that the publicity work done by the British Electrical Development Association has played an important part, since a large amount of the Association's Press-advertising during this period has been devoted to promoting the idea of electric water heating.

Types of Electric Water Heaters.

It is evident that many speakers thought the electric geyser was dismissed too summarily in the paper, but the hot-water output attributed to it was the maximum that can be obtained, i.e. at 100 % efficiency, and, owing to loss of heat in the lengthy process of filling a bath by this method, the useful amount of hot water available will be even less than the figure given by Mr. Gray.

Mr. Fella asked whether a 4-kW geyser might not have some useful application in place of a $1\frac{1}{2}$-gallon storage heater. It is true that some geysers of this size are in use in doctors' surgeries and other places where small quantities of hot water are only required at infrequent intervals, but for general use they will not give such a copious supply as a storage heater; while it will be seen from a later section of the paper that their load characteristics cannot be so acceptable to supply authorities, who would not be justified in hiring out this type of heater. Moreover, it is not correct to assume, as Mr. Minter appears to do, that the design of a reliable geyser is a simple matter. In general, this type of heater is not regarded by those with experience as capable of giving satisfactory hot-water service; cheaply-made geysers may in fact be a menace to the user, owing to danger of shock.

Self-Contained Heaters.

The British Standard Specification for "Thermostatically Controlled Electric Water Heaters" (No. 842—1939), which has since been issued, will undoubtedly serve a useful purpose, as suggested by Mr. McKenzie and Mr. Humphreys. I accept Mr. C. H. Smith's suggestion that the term "vent pipe" is preferable to

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* B.E.D.A. Report No. 1338 (Domestic Water Heating).

"expansion pipe," although the latter is in general use, probably because hot water in the pipe, owing to expansion, stands at a higher level than the water in the ball-valve feed tank.

Water Container.

With regard to the debatable point whether copper containers should be tinned, the discussions reveal a majority of opinion in favour of tinning, and I agree with this view as far as heaters of the non-pressure or cistern types are concerned, in which there is an air-water line; I also agree with it so far as small sizes of heaters are concerned, water from which will be used for culinary purposes. As regards other water containers, however, the need for tinning is not imperative for all waters. Many untinned copper cylinders have been in satisfactory use for a long time.

Heating Element.

The remarks on standard loadings of elements show, as was stated by Mr. C. H. Smith, that these are satisfactory for all-round purposes. They may have to be increased where space does not permit the ideal size of tank to be installed or, as was mentioned by Mr. Millner, for certain commercial premises. On the other hand, as was stated by Mr. Ward and others, lower loadings can often be installed without detriment to the hot-water service, in which case the supply authority obtains better load characteristics.

Thermostat.

It is accepted that a high thermostat setting such as 190° F., which may be used with soft water, is only of advantage in that it gives a maximum amount of stored heat—for example, 15½ gallons at 190° F. is equivalent to 20 gallons at 160° F.—and this is an important factor in regard to the installation of self-contained heaters, not only as regards capital cost but also on the score of space-saving.

Experience does not indicate that a high thermostat setting is a danger, as feared by Mr. Parker; but the heat loss is somewhat increased as compared with that of the larger quantity of hot water which has to be stored at a lower temperature to give the same heat content, because the heat stored varies as the cube, whereas the heat loss varies as the surface of the container.

Questions raised in regard to a suitable thermostat setting for use with hard water are dealt with below, and reference is also made later to the effect of the temperature gradient between the top and the bottom of the water contained in a cylinder; but this aspect so far as it affects the design of self-contained water heaters, as discussed by Mr. Humphreys and Mr. Gartside, may be summarized as follows. In any heater there is a certain temperature gradient, depending partly upon the size and shape of the containing vessel and other factors such as a draught tube which will affect the internal circulation; but, other things being equal, the temperature gradient will be principally affected by the arrangement of the heating element. If the element is situated at the base of the heater, the temperature gradient will be very small—an extreme example of this being the electric kettle where, owing to rapid circulation, the whole of the contents boils at the same moment. On the other hand, if the element is at the top of the container, since hot water will not descend, the circulation will be non-existent or sluggish, with the result that a steep temperature gradient will exist. While this is objectionable because of the lower average temperature of the water, it is an advantage in providing quick recuperation for small quantities of hot water at the top of the container after the whole of the contents has been drawn off. For this reason, and also to comply with the exigencies of space, the heating elements in the smaller sizes of self-contained water heaters usually extend upwards from the apparatus plate for some considerable proportion of the total internal height, so that an appreciable temperature gradient exists. The setting of the thermostat will then depend upon its length, in the way described by Mr. Humphreys and Mr. Gartside. Common practice is to use a fairly long-stemmed thermostat, which generally lends itself to the best compromise in design.

Lagging and Heat Losses.

Fig. 3, on which several questions were asked, was included to illustrate the heat loss through various thicknesses of lagging of a 1½-gallon heater maintained at 170° F. with 55° F. ambient temperature; in addition there is, of course, considerable loss from the apparatus plate and fittings.

In regard to heat losses from self-contained water heaters, support for the figures given in the paper is provided by the new British Standard Specification No. 843—1939, which gives only slightly greater values as maxima.

Small Heaters.

Table 4 was merely intended as a representative illustration of the everyday use of a 1½-gallon sink heater, which is confirmed, for example, by Mr. Ward. Despite the surprise expressed by several speakers that the water should be used for culinary purposes, this practice is followed in thousands of houses with every satisfaction.

As mentioned by Mr. Ward, the problem of designing a good anti-drip device is not yet fully solved, but it is a matter which is constantly engaging the attention of manufacturers, and improved designs may be expected. In any case I would not agree with Mr. Eden that a pressure type of heater is to be preferred on this account, since the loss from the expansion pipe would probably be greater than the small amount of hot water wasted by the slight imperfections of existing types of anti-drip devices.

Designs suitable for Hard Water.

As the discussion showed, the problem of designing small heaters which will not suffer from excessive deposits of scale is probably the most important aspect of the whole subject for those who have to deal with hard-water districts. I am indebted to Mr. Edgell for giving so much information about his experience at Gloucester, where the water is not only very hard but also appears to cause a form of scale which is particularly adherent and difficult to deal with.

In general, two methods of dealing with scale formation have been developed. The first—and probably the simpler—is to design the heating elements so that they descale themselves.

The second is to design the whole water heater so that scale formation is avoided as far as possible or so that there is a type of scale formed which can be carried away with the water.

One of the best-known solutions by the first method is a highly loaded element which, by movement during heating and cooling, will crack off the scale deposited on the surface. It is well known that this method is entirely effective in preventing deposits of scale from building up to a dangerous thickness when used in many different kinds of water of medium hardness. In obtaining the best results it is of assistance, as suggested by Mr. Scott, to make the general shape of the element such that it is deformed as much as possible by thermal expansion and contraction. The deformation of the cross-section, however, plays a greater part than Mr. Newman suggests because, although scale is strong in compression, the element tube inside it contracts in a water heater owing to cooling (though probably not in the marine evaporator mentioned by him), thus tending to separate the scale from the element.

Even when deposition of scale on the element can be avoided in this way, the accumulation of scale in the interior of the heater may be a serious matter and, although the easily removable design of outlet tube mentioned by Mr. McKenzie reduces maintenance work, it would clearly be better if scale formation could be prevented. The easiest way of doing this is to reduce the temperature of the water, but, as was pointed out by several speakers, some waters deposit scale at temperatures as low as 130° F. so that this is not a complete remedy in all cases. Another straightforward method of dealing with waters that are not too hard is to reduce the loading of the element to a value of, say, 10 watts per sq. in. of element surface. The results of Mr. Edgell's experience show, however, that in dealing with some very hard waters there are other factors which may have an even greater effect.

In order to explain these factors the chemical and physical actions taking place when hard water is in contact with the heating surface must be understood. I am generally in agreement with the explanation given by Mr. Sanders, and I believe the following description represents the actions taking place. Chemical analysis of scale discloses calcium carbonate as a principal salt precipitated, but the salt contained in the water is probably the soluble calcium bicarbonate $Ca(HCO_3)_2$. The molecules of this, also the similar magnesium salt, are held in solution by CO_2 molecules. The latter, however, have a tendency to break down with increasing temperature, particularly when accompanied by agitation or shock:—

$$Ca(HCO_3)_2 + \text{Heat} = CaCO_3 + CO_2 + H_2O$$

The evolution of CO_2 is therefore accompanied by the formation of the insoluble carbonate. This action is brought about by heat or shock and, as Mr. Edgell says, it is important to design the heater so that the heated water does not flow up a long vertical heating element. Such an element will not only cause a greater temperature-rise towards its upper end but will also promote a rapid turbulent convection flow. This theory is borne out by a comparison of the No. 3 and No. 4 heater interiors which Mr. Edgell exhibited, the taller element (in No. 3) showing greater scale deposit (mostly at its upper end) than the heating element in No. 4, which was only half the height of that in No. 3. This is also the general experience with immersion heaters fitted to existing hot-water tanks, where a horizontal position invariably leads to less deposition of scale than a vertical position. In addition to the question of avoiding deposit of scale on the heating element, it is almost of equal importance to ensure that the outlet tube, thermostat stem, and other interior parts, are not subject to scale formation. The No. 1 heater interior to which Mr. Edgell refers had a reasonably small deposit on the heating elements (these having a heat density of only 5 watts per sq. in.), but the top end of the outlet tube became choked with scale because the mushroom cap with which it was fitted was very near the ascending flow of hot water from the heating elements and thus caused turbulence which deposited scale.

It is on these grounds that the top-outlet type of heater illustrated at (*a*) in Fig. 5A of the paper has been found to be free from scaling of the outlet tube. When the outlet tube takes the more usual form of a stand pipe it should be of large diameter, of uniform bore, and free from any fitting which would cause turbulence. In the same way the inlet baffle should be designed to give as smooth a flow of water as possible.

Another factor which plays a part in determining the amount of scale which will be deposited in a heater is the type of crystal formation. Calcium carbonate is found in nature in widely different crystalline structures; as aragonite it occurs in needle-like crystals, while as calcite or calspar the crystals are shaped more like a cube. Other varieties are known, such as satinspar, which in the mass has a fibrous structure. Examination of scale deposits shows that the formation of calcium carbonate in a water heater exhibits similar variations and that some varieties adhere more strongly than others. Moreover, the variation in character of scale deposit with different heaters using the same water indicates that the temperature and perhaps the surface finish of a heating element has an effect on the texture of the scale formed. Recent investigation leads to the hope that, in future, heaters may be designed in which such scale as is formed remains in suspension in the water and is carried away, leaving no deposit inside the heater; but research on these lines is made all the more difficult by the variation in scale-forming propensities of different waters.

Cistern-type Heaters.

I regret that Mr. Osborne and others did not appreciate that, in referring in the paper to the pressure in a cistern-type heater being limited to the head of water between the bottom of the container and the top of the ball-valve tank, I was considering only the internal pressure, in so far as it refers to the question of whether a rectangular shape is permissible. The size of feed pipe necessary depends, of course, upon whether the heater is of the constant-temperature or the constant-volume type.

Immersion Heaters and Circulators.

As might be expected, the design of the heating elements for fitting in existing hot-water tanks and cylinders gave rise to a considerable amount of discussion. The most controversial point is whether the heating element should be mounted horizontally at the bottom of the tank or in the top, more or less vertically downwards. Any prominence given in the paper to the latter arrangement arose from its wide use in the North of England, where hand control is often employed in small houses. Evidence was given by Mr. Lee and other speakers of the small size of cylinders in general use, and, as is mentioned in the paper, in such cases it is particularly important to install a type of circulator which will give thorough heating of the whole contents of the cylinder. Figs. 6A and 6B were included in the paper merely as an illustration of the necessity to adopt some design of circulator different from the plain uniformly-wound type, and the performance, as shown in the broken lines, does not necessarily represent the best results that can be obtained. Since the action of the thermostat was questioned by several speakers, I would point out that, as is stated in the explanation of Fig. 6A, the same thermostat (18 in. long, set at 150° F.) was used in connection with both heaters. The arrangement of the thermostat does, of course, play an important part in the practical results obtained—Mr. Grierson's experience of unsatisfactory operation of circulators is a case in point—but Fig. 6A was primarily given to show the temperature distribution during the heating-up period, which is independent of the action of the thermostat. A longer thermostat, or one which is only sensitive over the lower part of its length, will naturally give a closer indication of the temperature towards the bottom of the cylinder, but unless the heating element is designed to avoid a large temperature-gradient, boiling may occur at the top before the water at the bottom is hot.

To sum up the comparison between circulators and immersion heaters, it may be said that the former are generally preferable for cylinders in which electric heating is used occasionally under hand control—in other words, when the method of use is to switch on for a sufficient length of time to heat the quantity of water required. This type of hot-water service is admittedly rather a primitive arrangement, but it may be all that the poorest class of consumer can afford. On the other hand, the horizontally fitted immersion heater is almost essential when the water is hard, owing to reduced scaling as described above in the section headed "Designs suitable for Hard Water." With the plain immersion heater, a greater amount of stored heat is obtained at the expense of quick recuperation, but the latter is not a serious objection when automatic control is employed; moreover, the recuperation at the top of a cylinder which is tall in comparison with its diameter may be quicker than might be supposed, a layer of hot water being formed at the top more easily than in a rectangular tank, the whole contents of which tend to be circulated by the action of the heating element.

I am indebted to Mr. Osborne for Fig. B, illustrating the performance of a side-entry circulator which combines quick recuperation with a large amount of heat storage, and appears likely to give satisfactory results with soft water.

Questions were raised by several speakers as to external (" side-arm ") circulators and belt-type heating elements. The former may sometimes be of advantage in soft-water districts for converting calorifiers, and the latter, if carefully fitted, may be of advantage with hard water; but both tend to suffer from increased radiation loss.

Lagging for Existing Tanks and Cylinders.

Other lagging materials, apart from granulated cork, were mentioned in the discussion; of these, glass-wool and crinkled aluminium foil have a lower heat loss but are more expensive in first cost. Red cedar-wood fibre, mentioned by Mr. Grierson, is easier to apply in some cases, but test results given by Mr. McLean show that the heat loss of this material is appreciably greater than that of cork. It is true that granulated cork " packs " slightly, but allowance can easily be made for this by filling the containing box to a slightly greater height than is actually required.

In reply to Mr. Eden's remarks on Fig. 9, I would point out that this relationship was only claimed to hold good for slight temperature-differences, for which the logarithmic cooling curve can be approximated to a straight line.

Automatic versus Hand Control.

Except for the very poorest class of user, I agree with Mr. Howarth and Mr. Onley that automatic control or a combination of hand and automatic control is desirable. The omission of a hand switch probably caused the unfortunate experience with automatic systems to which Mr. Rawll refers. I do not agree, for reasons given in the paper, with the policy of making thermostatic control or lagging the subject of an extra charge or some differentiation in the terms of payment, and Mr. Swale's experience supports this view. As Mr. J. L. Carr remarks, " the ultimate aim should be to provide a continuous supply of hot water." The use of electric heating merely for boosting purposes is not likely to bring about the greatest appreciation of the service by the user.

For some borderline cases, especially where there is no existing hot-water system, the use of the highly loaded unlagged type of heater mentioned by Mr. Ashton and Mr. Cockram finds a useful place, particularly if its capital cost can be justified in addition to that of a 1½-gallon heater for the kitchen sink.

Mr. Grierson and Mr. McLean refer to the question of airing cupboards; with regard to the comparison made by Mr. McLean between the running cost of an electrically-heated towel rail and the increased running cost which is likely to result from removing part of the lagging of an electrically-heated tank, I would point out that the towel rail need only be switched on for a few hours of the day. The capital cost of a towel rail was not included in the paper, but, as Mr. Gray says, a short length of tubular heater is a cheap alternative.

Installation Practice.

Considerable discussion took place on installation problems and space does not permit of reference to all the detailed points, some of which were answered by other speakers. I agree that there may be some danger due to electrolytic or other deleterious action if copper pipes are used with galvanized-iron tanks; it is fortunate from this point of view that the use of copper cylinders appears to be increasing in parts of the country where iron tanks were previously used.

In regard to the reduction of heat loss from expansion pipes, the method described in the paper of arranging a short horizontal length is generally effective for the larger sizes of iron pipe. For smaller copper pipes, however, there is greater loss by conduction which probably explains Captain Coxon's experience. There is danger in dipping the pipe because this may lead to an air lock, as described by Mr. Sanderson.

As regards the installation of a separate water heater at the point of use in preference to a long length of hot-water piping, each case must be considered on its merits. The figures given in the paper were quoted as an example of the order of magnitude of the losses involved.

Several speakers doubt the practicability of converting calorifiers, but, as is pointed out in the paper, space can easily be found for the fitting of one type of immersion heater or another and, as regards the possibility of heat loss in the primary circulation system of the boiler, there is usually no likelihood of this taking place when both flow and return pipes follow a downward path from the calorifier as shown in Fig. 11. If, however, the calorifier is very tall, or has sufficient temperature-gradient to give a difference of temperature between the top and bottom of the calorifier which will cause primary circulation, a gate valve should be fitted in the primary circuit to be closed when the electric heating is in use. A valve must also be fitted, of course, if the primary return pipe follows an upward course to supply radiators in series with a calorifier instead of in parallel as shown in Fig. 11.

With regard to Mr. Grierson's criticism of the statement in the paper that hot water will not circulate downwards, perhaps this should have been qualified by saying that hot water will only flow downwards if it is first made to flow upwards.

Electricity Supply Policy.

The first point that arises on this section of the paper is the question of high versus low loading of heaters. Study of the load curves of an undertaking supplying residential areas shows that peak-load times are not sufficiently definite nowadays for there to be much hope that highly-loaded heaters will always be switched off at times of maximum demand, as suggested by Mr. Grierson. One is therefore forced to the conclusion that reliance can only be placed on the general characteristics of the load; and test results show, as illustrated in Fig. 15, that low-loaded heaters give much better load characteristics.

I agree with Mr. J. L. Carr that the load characteristics of hand-controlled circulators appear to be more akin to those of the radiator load than to those of the storage-heater load. Mr. Rawll suggests that the load characteristics of the whole domestic load should be investigated, but if improvement in this direction is to be obtained the load characteristics of the components—such as cooking, space heating, and water heating—need to be studied separately; and, as water heating has the inherent advantage of energy storage, I suggest that further study of its load characteristics is desirable.

At the same time, I do not agree with Mr. Rowson's sweeping strictures on the electricity supply industry, which, as he must know, is already supplying less remunerative loads than water heating at prices which are lower than those charged in America. Nor is the experience in New Zealand, to which he refers, a safe guide to probable developments here, since the load in that country is almost entirely composed of special water heaters used in dairy work. It is also beside the point to discuss the way in which water heating might overshadow other loads, since sound economic development must be based on a rational expansion of all classes of supply. The benefit of devoting more attention to electric water heating than has so far been given to it by some supply undertakings in this country can be seen from a study of results obtained at Basle, Amsterdam, and other places.

It is generally agreed that no restriction of electricity supply which would interfere with the hot-water service to the user can be tolerated. Incidentally, Mr. Cunliffe puts forward a rather ingenious method of making a modified form of restriction more acceptable to the user, but I am doubtful whether this would be satisfactory in practice, primarily because most electric water-heating installations should be under automatic and not hand control, and, secondly, because even energy at a discount would probably be regarded, in effect, as a restriction of the service.

The methods of load-levelling mentioned by Mr. Eden and Mr. Roberts are only of advantage in reducing the demand on the service cable and on the distribution system in the immediate vicinity, and do not help to improve the general load characteristics of the whole system.

I appreciate Mr. J. L. Carr's opinion that ultimately the need for time control will be demonstrated. Mr. Hallowell's experience of the practical application of a ripple control system is of great interest, although I do not agree with his analysis of the cost of supplying a 2-kW water heater, because the maximum demand of 0·95 kW, after allowing for diversity, may not, and in most cases does not, coincide with the chargeable maximum demand either on the distribution network or on the whole system.

As was mentioned by Mr. Osborne, the installation of ripple control systems will enable the characteristics of the water-heating load to be determined throughout the day, and the results of tests of this kind will be awaited with interest.

THE EVALUATION OF TRANSIENT TEMPERATURE DISTRIBUTIONS IN A DIELECTRIC IN AN ALTERNATING FIELD*

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SUMMARY

For many solid dielectrics the rate of generation of heat in an alternating electric field increases approximately exponentially with the temperature. For such materials, not only the condition for a steady state and the temperature distribution in it, but also the time variation of the temperature, both when a steady state exists and when the field is above the critical field for which thermal instability occurs, is of interest and importance. The present paper is concerned with the process of evaluating, for the transient case, the solution of the equation of heat conduction in one dimension for such a material, and gives some results.

The solutions evaluated are believed to be the first calculated for a non-linear variation of generation of heat with temperature, and show a close correspondence with the results of tests on actual materials. Particularly the ultimate catastrophic rise of temperature, in fields just above the critical field which leads to breakdown, is clearly shown by the solutions. This behaviour cannot occur if the rate of generation of heat varies linearly with temperature, but these results show that it is unnecessary to postulate any other cause (such as deterioration) beyond the exponential variation of heat generation with temperature to account for it.

CONTENTS

(1) Introduction.
(2) Equation for Transient Temperature Distribution, and its Reduction to Non-Dimensional Form.
(3) Process of Solution of Equation for Transient Temperature Distribution.
(4) Results.
(5) Discussion of Results.
(6) Acknowledgments.
Appendix I. The Steady State.
Appendix II. Application of the Differential Analyser.
  (*a*) Machine Set-up.
  (*b*) Procedure.
Appendix III. Starting the Integration.

(1) INTRODUCTION

The variation and distribution of temperature in a material in which heat is being generated at a rate which depends on the temperature is a subject of considerable technical importance. It arises in both the testing and use of solid insulating materials, since the power loss, and consequent heat generation, which such materials exhibit in varying degrees in alternating electric fields is usually found to increase continually with the temperature. In using these materials it is necessary to restrict the maximum temperature-rise within the body of the material to a safe value at which the material can withstand the applied electric stress continuously; in other words, to ensure that it is thermally stable. It is therefore of interest to consider the way in which such a steady state is attained, and the temperature distribution associated with it.

It is also of interest to examine the variation and distribution of temperature under conditions of applied electric stress in which thermal instability arises, i.e. under which the maximum temperature in the material never reaches a steady value but continues to rise until it attains a value at which the intrinsic electric strength of the material becomes less than the applied stress, and breakdown occurs. The time required for breakdown to occur will clearly depend on the degree to which the critical condition for thermal instability is exceeded, and the relation between these quantities may be of interest in giving limits to the time for which it is safe for the material to be overstressed to different degrees.

Thus means of evaluating the solution of the equation of heat conduction in a substance in which heat is being generated, at a rate depending in a definite way on the temperature, would be of some technical value and importance. It does not yet seem practicable to evaluate such a solution, even for a steady state, except for simple geometrical shapes of the boundary. But, for the geometrically simplest special case in which the flow of heat is one-dimensional, it has been found possible to obtain solutions, not only for the steady state, but for transient cases, in which the temperature distribution varies with time; and a few such solutions and the means of evaluating them may be of some interest.

For a rate of generation of heat which, for a given field, increases linearly with the temperature, the equation of heat conduction is linear and, for simple boundaries, can be solved formally; a solution for the one-dimensional case of a slab with faces kept at constant temperature has been given by Goodlet, Edwards, and Perry.‡ But it follows from these authors' results that, although for fields above the critical field (dependent on the specimen) thermal instability would occur, this instability would be something very different from the catastrophic breakdown which occurs for actual materials. If the field is only slightly greater than the critical field, then for a linear variation of the rate of heat generation with temperature, the temperature ultimately increases as e^{bt}, where b is proportional to the excess of the field above its critical value.[*] This is a very slowly increasing exponential if this excess is small, though in course of time the temperature would reach such high values that actual materials would suffer physical or chemical deterioration [drying, charring, etc.] which would lead to breakdown.[†]

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* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

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‡ See Reference (1). See articularly Appendix III (p. 726).

For an actual material in a field above the critical field, on the other hand, the temperature may increase slowly for a long time, but ultimately a stage is reached at which it begins to increase rapidly and then catastrophically; moreover, this behaviour may be repeatable with a single specimen so long as breakdown has not actually occurred, showing that the behaviour is not merely an effect of deterioration of the material.[‡] Since the catastrophic breakdown characteristic of actual materials does not arise when the rate of generation of heat increases linearly with the temperature, but requires a more rapid rise (that is to say the curve of the rate of generation of heat against temperature must have an upward curvature), it follows that any theoretical investigation of this behaviour will involve the solution of a non-linear form of the equation of heat conduction.

This equation, in one dimension, with boundary conditions of the kind which will generally occur in cases of practical interest, is a partial differential equation in two variables of a type that can be handled by a method which has recently been discussed by one of us,[§] and which, since it is not restricted to linear equations, can be used in cases in which the variation of the rate of generation of heat with temperature is such as appears necessary to account for the breakdown phenomena observed. This method is very well suited to mechanical integration by the differential analyser of Dr. Bush,[||] and the work described in the present paper was done as the first experiment in the application of the differential analyser to this method of the solution of partial differential equations. For some of the work only a rough form of the method was used, as the work was intended to be exploratory, rather than to obtain precise results. But the results, such as they are, are interesting both as showing a qualitative agreement with the behaviour of actual materials, and as illustrating the possibility of applying the differential analyser to problems of this kind.

(2) EQUATION FOR TRANSIENT TEMPERATURE DISTRIBUTION, AND ITS REDUCTION TO NON-DIMENSIONAL FORM

Consider the one-dimensional flow of heat in a specimen consisting of a parallel-sided slab of material. Goodlet, Edwards, and Perry[¶] have shown that for many solid dielectrics in an alternating field of intensity E, the rate of generation of heat per unit volume, G, at temperature θ can be expressed closely by the formula

$$G = \alpha E^2 e^{\gamma\theta} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where α and γ are constants characteristic of the material. This relation is only an empirical one and is only approximate, and in real materials the variation of temperature through the slab may result in a non-uniform distribution of electric stress; but for simplicity, and to restrict the number of parameters on which the solution depends, it will be supposed that the rate of generation of heat is given exactly by (1), and that E is constant through the slab. The present work is not concerned with the mechanism of such a rate of generation of heat, but with its consequences, as shown by the variation and distribution of temperature in the slab. In particular, it is of interest to examine whether such a generation of heat is adequate to account for the time variation of the temperature actually observed in real materials.

If the material is of specific heat c, density ρ, and conductivity k (all of which are assumed to be constant), the equation of heat conduction with a generation of heat given by (1) is

$$c\rho\frac{\partial\theta}{\partial t} = k\frac{\partial^2\theta}{\partial x^2} + \alpha E^2 e^{\gamma\theta} \quad . \quad . \quad . \quad . \quad (2)$$

The boundary conditions for the solution will usually be the temperature distribution through the slab at $t = 0$, and terminal conditions at the two faces of the slab for all time; these conditions will usually be in the form of given temperatures or given rates of heat transfer, or given relations between these quantities, at the two faces.

In order to show to what extent the results are independent of the dimensions and characteristics of a particular specimen, it is convenient to reduce the equations to non-dimensional form. If θ_0 is the ambient temperature and l is a typical length, and we use the non-dimensional reduced variables

$$\phi = \gamma(\theta - \theta_0), \quad \xi = x/l, \quad \tau = (k/c\rho l^2)t \quad . \quad . \quad (3)$$

equation (2) becomes

$$\frac{\partial\phi}{\partial\tau} = \frac{\partial^2\phi}{\partial\xi^2} + \beta e^{\phi} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where
$$\beta = \gamma\alpha e^{\gamma\theta_0} E^2 l^2/k \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Thus a set of solutions of (4) with the same initial conditions, for different values of β, will apply not only to a single specimen in different fields E but also to a range of specimens of different sizes and materials.

The work here reported has been concerned with the solution of (4) with the simplest boundary conditions, namely the initial conditions

$$\phi = 0 \text{ at } \tau = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

and the terminal conditions

$$\phi = 0 \text{ at } \xi = 0, \ \xi = 4$$

(so that the typical length l is a quarter of the thickness of the slab), or the equivalent conditions

$$\phi = 0 \text{ at } \xi = 0; \ \frac{\partial\phi}{\partial\xi} = 0 \text{ at } \xi = 2 \quad . \quad . \quad . \quad (7)$$

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[*] This follows formula (14) of Reference (1).

[†] As Goodlet, Edwards, and Perry [Reference (1)], point out, even for fields just less than the critical field it is possible that the temperature would rise so high as to cause such deterioration, although formally there is no true thermal instability. Such deterioration might be expressed formally by a variation in the coefficients in the assumed linear relation between temperature and rate of generation of heat, but such a variation of coefficients is really an indirect way of expressing a non-linear relation.

[‡] See, for example, Reference (2), particularly pp. 35–38.

[§] See Reference (3). [||] *Ibid.*, (4). [¶] *Ibid.*, (1).

It would be perfectly practicable to carry out the solutions for other forms of boundary conditions, but these seemed the simplest for a first trial of the method. This choice of boundary conditions reduces the number of independent parameters on which the solution depends to one, namely β. A symmetrical case with Newton's law of cooling at both surfaces, which would correspond more closely to practical situations, would involve two independent parameters, namely β and the reduced value of the coefficient relating temperature gradient and the temperature itself at the surface.

The solution of equation (4) with $\partial\phi/\partial\tau = 0$ is enough to establish whether a steady state is possible, and the temperature distribution in such a state, and such investigations have been carried out by Dreyfus and others for more general boundary conditions.* But by the nature of the case such an investigation can neither show how the steady state is approached, nor give any information as to the behaviour of the temperature when no steady state is possible, and the determination of this transient behaviour has been the main purpose of the present work.

However, in order to get some idea of the values of β for which to attempt solutions for the transient case, it is necessary first to consider the steady state.

This is done in Appendix I, where it is shown that for these boundary conditions the critical value β_0 of β, above which no steady state is possible, is $\beta_0 = 0{\cdot}220$. It is also shown that the value of ϕ_c, the reduced temperature at the centre of the slab, is then $\phi_c = 1{\cdot}19$.

Taking Goodlet, Edwards, and Perry's values for a "poor" material, for example, namely†

$$k = 1{\cdot}6 \times 10^{-3}\,(\text{watts per cm}^2)/(\text{deg. C. per cm.})$$

$$\alpha e^{\gamma\theta_0} = 30 \times 10^{-6}\,(\text{watts per cm}^3)/(\text{kV per cm.})^2 \text{ at } 90^\circ\text{ C.}$$

$$\gamma = 2{\cdot}7 \times 10^{-2}\,(\text{deg. C.})^{-1},$$

we have:—

Limiting voltage across slab $= 4El = 84$ kV.

Limiting central temperature above ambient temperature

$$\theta_c - \theta_0 = \phi_c/\gamma = 44^\circ\text{ C.}$$

It should be noted that the field E and the thickness l of the specimen occur here only in the combination El; this is a consequence of the ideal boundary conditions taken.‡ Another result worth noting is that the limiting value of $\theta_c - \theta_0$ depends only on γ and not on other characteristics of the specimen.

(3) PROCESS OF SOLUTION OF THE EQUATION FOR THE TRANSIENT TEMPERATURE DISTRIBUTION

The process of solution used to evaluate the transient temperature distribution, to which reference has already been made, depends essentially on replacing the partial differential equation (4) approximately by an ordinary differential equation, by replacing the time rate of change of temperature at each point by the change of temperature in a finite interval of time, while retaining the space derivatives. This ordinary differential equation can then be solved, and a correction can subsequently be applied for the error made in replacing the time rate of change by the change in a finite time-interval.

Writing suffixes 0 and 1 for the values of quantities at $\tau = \tau_0$ and at $\tau = \tau_1 = \tau_0 + \delta\tau$, we can replace $\partial\phi/\partial\tau$ by $(\phi_1 - \phi_0)/\delta\tau$, and, to the same approximation, we can replace $\partial^2\phi/\partial\xi^2$ by $\frac{1}{2}[(\partial^2\phi_1/\partial\xi^2) + (\partial^2\phi_0/\partial\xi^2)]$ and so on, so that (4) can be replaced by*

$$\frac{\phi_1 - \phi_0}{\delta\tau} = \frac{1}{2}\frac{\partial^2}{\partial\xi^2}(\phi_1 + \phi_0) + \frac{1}{2}\beta(e^{\phi_1} + e^{\phi_0}) \quad . \quad (8)$$

Alternatively, to the same order of approximation, the heat-generation term βe^{ϕ} can be replaced by the geometric mean of its values at the beginning and end of the time interval, instead of by the arithmetic mean; and (4) replaced by

$$\frac{\phi_1 - \phi_0}{\delta\tau} = \frac{1}{2}\frac{\partial^2}{\partial\xi^2}(\phi_1 + \phi_0) + \beta e^{\frac{1}{2}(\phi_1 + \phi_0)} \quad . \quad . \quad (9)$$

which happens to be more convenient for setting up on the differential analyser. The initial temperature distribution, that is to say ϕ_0 as a function of ξ, is known, and this is now an ordinary differential equation for the final temperature distribution ϕ_1 as a function of ξ.

The final temperature distribution ϕ_1 for one time-interval $\delta\tau$ then becomes the initial temperature distribution ϕ_0 for the next.

Further, it is possible to correct for the main part of the error introduced by replacing (4) by (9). This is done by covering the same range, say from $\tau = 0$ to T, by two independent integrations, one with intervals $\delta\tau = \Delta$ and the other with intervals $\delta\tau = 2\Delta$. The temperature ϕ at a given place ξ and time τ, calculated by the solution of the approximate equation (9), will depend on Δ as well as on ξ and τ; it can be shown† that the leading term in the error is proportional to Δ^2 and so is 4 times as large for the calculations with the large intervals as with those for the small intervals. Thus from the two separate integrations the error in each can be estimated and allowed for. It is clear that in order to apply this process an even number of intervals must always be taken at the small τ-spacing. This refinement was only used in part of the work with which we are here concerned, since a trial showed that with the size of τ-interval used this correction for the finite size of the interval was usually small, and, as already explained, the present work was regarded as exploratory rather than as intended to give accurate solutions of the equation.

The application of the differential analyser to the evaluation of the solution of equation (9) is considered in Appendix II.

The solution of (4) with boundary conditions (6), (7) has a singularity at $\tau = 0$, and although the singularity is not a very severe one its presence means that the process of correction for the finite length of τ-interval is not valid in its neighbourhood, so it is advisable to get away from $\tau = 0$ before starting the mechanical integration. This can be done, since for small τ, while the temperature-rise is still small, the exponential e^{ϕ} in the term in (4) expressing the rate of heat generation can be replaced to adequate accuracy by 1 or by $(1 + \phi)$, and a formal solution of the equation can then be found and evaluated (see Appendix III).

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* See, for example, References (5), (6); also Reference (1), pp. 716–17.

† See Table 8 of Reference (1).

‡ Cf. Reference (1).

* It is not necessary here that the variation of the rate of generation of heat with temperature should be exponential; the argument would apply whatever the law of this variation.

† See Reference (3) for a fuller investigation.

(4) RESULTS

Solutions of (4) have been carried out for the three cases $\beta = \frac{1}{8}, \frac{1}{4}$, and $\frac{1}{2}$. The cases $\beta = \frac{1}{8}$ and $\frac{1}{2}$ were chosen for the first experimental work, to try out the method and see the general behaviour of the solutions. For both these cases the integration was started from $\tau = \frac{1}{4}$, and the partial differential equation was replaced by the ordinary differential equation (8). For $\beta = \frac{1}{8}$ the temperature distribution at $\tau = \frac{1}{4}$, from which the integration was started, was calculated from formula (23) (see Appendix III); the greatest value of ϕ at this value of τ was 0·03 and, to the accuracy of the input plot for the machine solution, it was not necessary to use a more accurate solution. For $\beta = \frac{1}{2}$, the initial temperature distribution was calculated from formula (24) (Appendix III). Figs. 1 and 2 show the time variation of the reduced central temperature ϕ_c; the plotted points show the τ-values at which the solution was evaluated, and the spacings between them show the sizes of interval used. An even number of intervals were taken at each τ-spacing, in preparation for the use of intervals of double size and the application of the correction for the finite length of interval mentioned in Section (3). But for the case $\beta = \frac{1}{8}$, trial with a single interval $\tau = \frac{1}{4}$

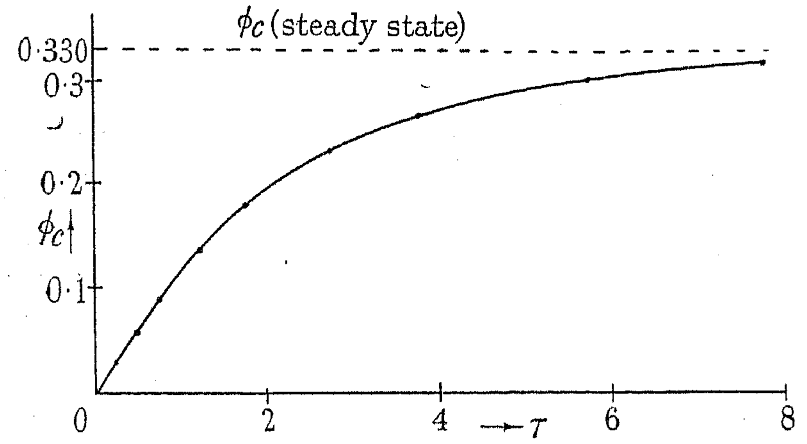

Fig. 1.—$\beta = \frac{1}{8}$. Calculated time variation of central temperature.

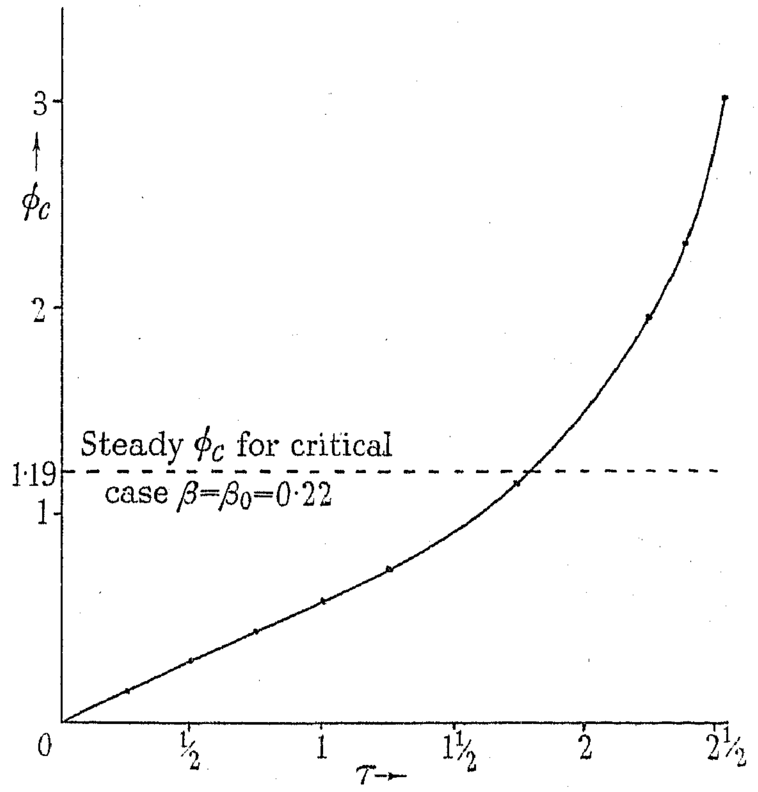

Fig. 2.—$\beta = \frac{1}{2}$. Calculated time variation of central temperature.

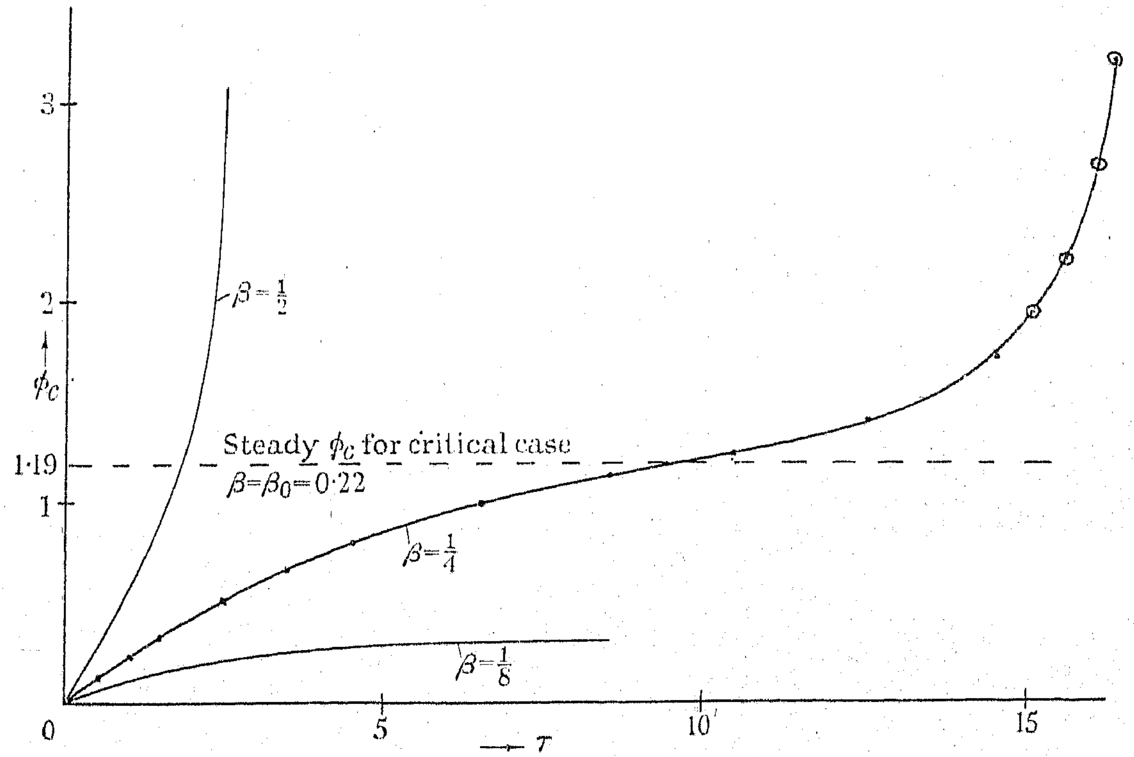

Fig. 3.—Time variation of central temperature. Calculated results for $\beta = \frac{1}{4}$, and curves for $\beta = \frac{1}{8}$ and $\frac{1}{2}$ drawn on same scale for comparison.

to $\frac{3}{4}$, and comparison with the results for the two intervals $\tau = \frac{1}{4}$ to $\frac{1}{2}$ and $\frac{1}{4}$ to $\frac{3}{4}$, showed that the correction for interval length was inappreciable for the intervals used, and this process was not used for either of these values of β, as it seemed unlikely that it would affect the general behaviour of the solutions.

For $\beta = \frac{1}{8}$, the central temperature was clearly approaching its steady value (shown in Fig. 1), and the solution was stopped at $\tau = 7\frac{3}{4}$; for $\beta = \frac{1}{2}$ it was increasing rapidly at $\tau = 2\frac{1}{2}$, and breakdown would clearly occur a very short time later.

A solution was then carried out for $\beta = \frac{1}{4}$, using equation (9). This value of β is only slightly above the critical value $\beta_0 = 0 \cdot 220$, so the behaviour of the solution was likely to be more interesting than for the other two cases, and, since it might also be more sensitive, it seemed worth while trying to evaluate it more accurately. The machine solution for this case was started from $\tau = \frac{1}{2}$, the temperature distribution at this time being calculated by numerical integration of equation (25) of Appendix III, following the method there explained.

Separate integrations were carried out for two different sets of time-intervals, namely one with $\delta\tau = \frac{1}{2}$ from $\tau = \frac{1}{2}$ to $4\frac{1}{2}$, and $\delta\tau = 1$ from $\tau = 4\frac{1}{2}$ to $14\frac{1}{2}$, and the other with double these intervals throughout; the corrections for finite τ-interval lengths were estimated by comparison of the results of these two integrations, and applied. The final results for the values of the central temperature ϕ_c are shown by the points plotted in Fig. 3; the correction for finite interval length is barely appreciable on the scale of this diagram.

At $\tau = 14\frac{1}{2}$ it was clear that the central temperature was beginning to increase rapidly; a few smaller intervals were taken to see roughly how it built up, but the correction for finite interval length was not applied. The points in Fig. 3 showing the resulting values of ϕ_c are ringed.

Curves showing the time variation of the central temperature for $\beta = \frac{1}{8}$ and $\frac{1}{2}$ (cf. Figs. 1 and 2) are reproduced in Fig. 3 on the same scale as the curve for $\beta = \frac{1}{4}$, for comparison.

Curves showing the calculated temperature distribution through the slab (or rather through half of it) for $\beta = \frac{1}{4}$ at successive times are shown in Fig. 4.

These results show that the application of the differential analyser to partial differential equations of this type is quite practicable. It should be pointed out, however, that the amount of work involved in obtaining even a single solution is considerable. A trial and error must be used for satisfying the terminal conditions (cf. Appendix II), and this means that each interval requires a large number of machine runs (as illustrated by Fig. 10), and altogether the number of runs involved in obtaining the solution for $\beta = \frac{1}{4}$ expressed by Figs. 3 and 4 is several hundred, so that such a solution is not to be undertaken lightly.

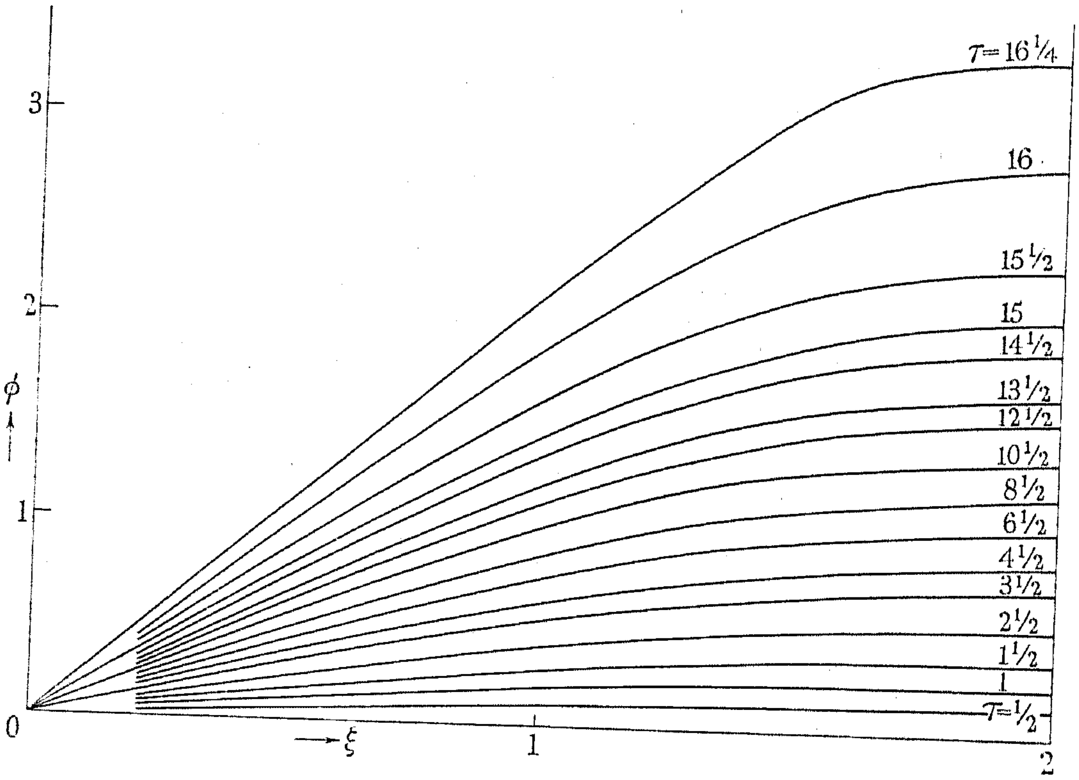

Fig. 4.—$\beta = \frac{1}{4}$. Calculated temperature distribution at different times.

(5) DISCUSSION OF RESULTS

The results expressed by Figs. 1–4 are of some interest as providing, as far as we know, the only results yet calculated for the transient behaviour of the temperature in a dielectric with a power loss increasing exponentially with temperature. They are in at least qualitative agreement with the known behaviour of electrical insulating materials in alternating fields; in particular the curve for $\beta = \frac{1}{4}$ in Fig. 3 is characteristic of the behaviour of such materials in fields just above the critical field which gives breakdown.

For comparison with the results of these calculations, Figs. 5 and 6 show results of experiments carried out in the Research Department of the Metropolitan-Vickers Electrical Co., Ltd., on specimens of poor-quality bakelite board under conditions approximating to the ideal conditions adopted in the evaluation of the solutions.

The experimental arrangement used is shown in

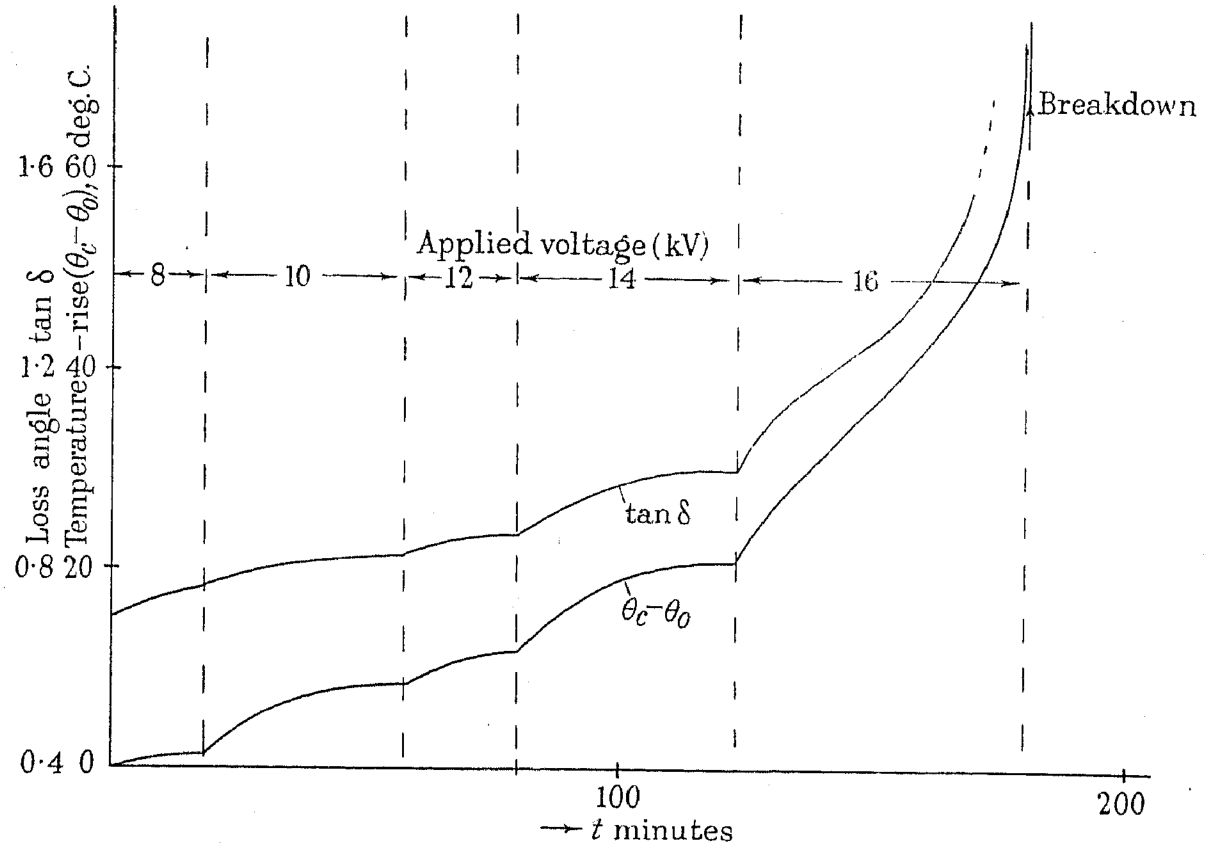

Fig. 5.—Observed time variation of central temperature and loss angle, for dielectric slab in field increased by steps of 2 kV.

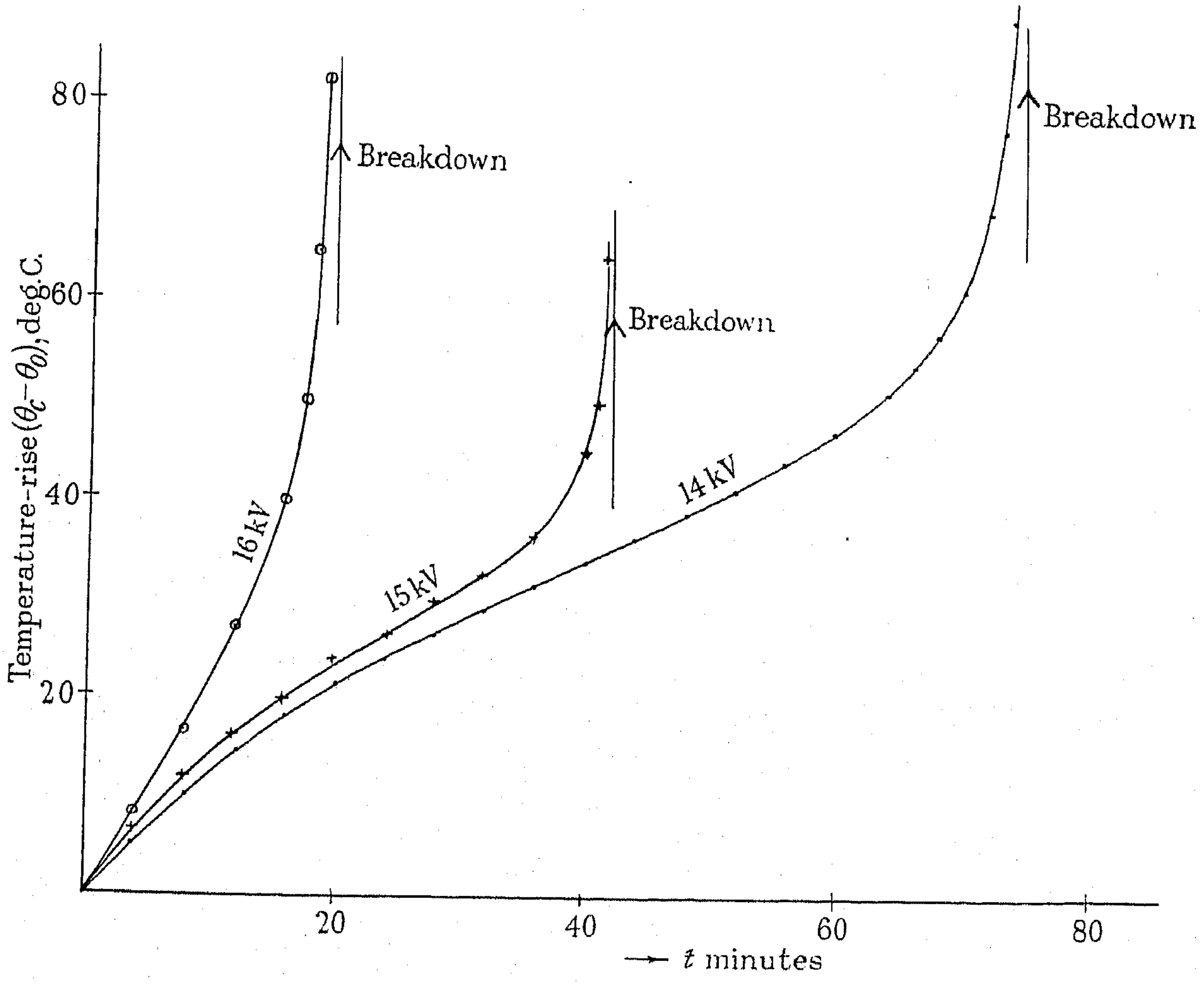

Fig. 6.—Observed time variation of central temperature for three specimens of dielectric, each in a constant field.

Fig. 7. Two 8-in. square pieces of board, $\frac{1}{2}$ in. thick, were separated at the centre by an earthed tinfoil electrode, and were clamped together between two 4-in. diameter brass-disc electrodes connected to the high-tension lead. The whole was supported under transformer oil maintained at a steady temperature of 90° C., and was allowed to attain this temperature throughout before the test voltage was applied. This high ambient temperature was adopted in order that breakdown would be likely to occur at voltages well below those for which sparking would take place round the edge of the boards. The temperature-rise at the centre of the dielectric assembly was measured by means of a thermocouple located at the earthed electrode.

Fig. 5 shows the time variation of central temperature θ_c and of tan δ, where δ is the loss angle, in an experiment in which the applied voltage was gradually increased by steps; the earlier portions of the curve of central temperature (e.g. the portion at 10 kV applied voltage) have very much the same form as the calculated curve given in Fig. 1. Fig. 6 shows the results of three experiments, each at a constant applied voltage; these suggest that for these specimens the applied voltage of 14 kV was just in excess of the critical voltage, corresponding closely to the condition for which the theoretical curve $\beta = \frac{1}{4}$ of Fig. 3 was calculated, and that the applied voltage of 16 kV was substantially in excess of the critical value, so that the resulting curve (*c*) has the general form of the calculated curve of Fig. 2.

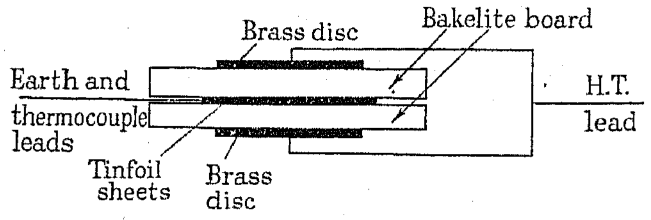

Fig. 7

These are the only available results known to the authors that have been carried out on thick specimens, so that the thermal resistance at the faces of the slab is probably small compared with the internal thermal resistance, and in which the central temperature has been measured. In tests of this kind it is more usual to measure the loss angle δ, which is a measure of the rate of generation of heat through the whole material, and so is related to some weighted mean temperature; though, since in this mean the central temperature will have the greatest weight, the loss angle can be taken roughly as an indication of the central temperature, as can be seen by comparing the curves for these two quantities in Fig. 5.

Qualitatively similar results are obtained on thin sheets of insulating material and some such have been published;* but in these the main thermal resistance is at the face of the material rather than in its interior, whereas for simplicity in these first experiments in the use of the differential analyser on partial differential equations we have taken the ideal boundary condition $\phi = 0$ at the faces of the slab. However, though the inclusion of a moderate thermal resistance at the faces would alter the quantitative results (for example, the critical value of β and the details of the behaviour of the solution), it would not be likely to alter the general nature of the solution, so that it is not surprising that experimental results on the loss angle of materials, under conditions in which the boundary thermal resistance is not too high, should be of the same general form.

The results shown in Fig. 3 show that a generation of heat at a rate increasing exponentially with the temperature is adequate to account for the kind of temperature variation observed in insulating materials in alternating fields. In particular, it accounts for the catastrophic rise of temperature preceding breakdown which occurs when the field is greater than the critical field for thermal stability, and which, as Goodlet, Edwards, and Perry have shown, cannot be explained on the basis of any linear relation between rate of generation of heat and temperature. In actual materials such a rise of temperature will, sooner or later, be accompanied by deterioration of the material, which will probably exaggerate the effect; but it is clear that it is not necessary to postulate such a change of properties in order to account for a temperature variation of the kind observed.

(6) ACKNOWLEDGMENTS

The authors wish to thank Prof. B. L. Goodlet for bringing this problem to their notice, and for his interest; Prof. W. Jackson for arranging for the experimental work referred to in Section (5), and for his interest and much valuable discussion; and Dr. A. P. M. Fleming, Director of Research at the Metropolitan-Vickers Electrical Co., Ltd., for permission to publish the results of the experiments. One of the authors (D. R. H.) wishes also to acknowledge his indebtedness to the Department of Scientific and Industrial Research for a grant for the employment of a research assistant for a programme of development and application of the differential analyser, of which this work forms a part.

APPENDIX I

The Steady State

For a steady state, equation (4) reduces to

$$\frac{\partial^2\phi}{\partial\xi^2} + \beta e^{\phi} = 0$$

which can be solved exactly as follows.

Multiplying by $2\partial\phi/\partial\xi$ and integrating, we have

$$(\partial\phi/\partial\xi)^2 + 2\beta e^{\phi} = 2\beta e^{\phi_c},$$

where ϕ_c is the reduced temperature at the centre of the slab, which will be determined later in the solution. The substitution

$$\cosh u = e^{\frac{1}{2}(\phi_c - \phi)} \quad . \quad . \quad . \quad . \quad (10)$$

gives

$$(\partial u/\partial\xi)^2 = \tfrac{1}{2}\beta e^{\phi_c},$$

whence, since $u = 0$ at the centre ($\xi = 2$),

$$u = (\tfrac{1}{2}\beta e^{\phi_c})^{\frac{1}{2}}(\xi - 2). \quad . \quad . \quad . \quad . \quad (11)$$

---

* See, for example, References (2) and (7).

But $\phi = 0$ at $\xi = 0$; hence from (10) and (11) the central temperature ϕ_c must be given by

$$\cosh\left[(2\beta)^{\frac{1}{2}}e^{\frac{1}{2}\phi_c}\right] = e^{\frac{1}{2}\phi_c}$$

The further substitution

$$(2\beta)^{\frac{1}{2}}e^{\frac{1}{2}\phi_c} = z$$

reduces this to

$$\cosh z = z/(2\beta)^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad (12)$$

so that z is given by the intersection of the curves of $\cosh z$ and $z/(2\beta)^{\frac{1}{2}}$ (see Fig. 8). It is clear that for values of β above a limiting value β_0 there will be no intersection and therefore no possible steady state; the corresponding value of the electric field E given by (5) is therefore the field above which thermal instability occurs with the boundary conditions considered. The critical value is clearly given by the condition that the root z_0 of (12) for $\beta = \beta_0$ should be a double root; this leads to the relations

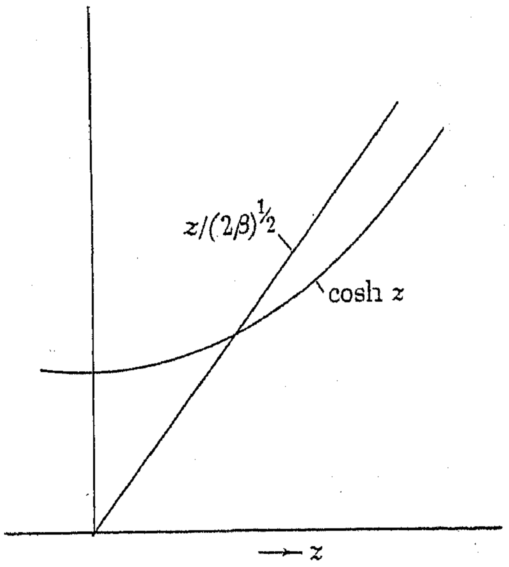

Fig. 8

$$\cosh z_0 = z_0/(2\beta_0)^{\frac{1}{2}}, \ \sinh z_0 = 1/(2\beta_0)^{\frac{1}{2}}$$

whence $z_0 = 1{\cdot}200$, $\beta_0 = 0{\cdot}220$. Also the reduced central temperature ϕ_c in the steady state in this limiting case is

$$\phi_c = 2\log_e \cosh z_0 = 1{\cdot}19.$$

APPENDIX II

Application of the Differential Analyser

(a) Machine Set-up.

The differential analyser is a machine for evaluating the solutions of ordinary differential equations. It consists of a number of integrators (each of which is a precision form of continuously variable gear), which can be interconnected by shafts and gearing so that the relation between the rotations between different shafts of the machine satisfies the equation to be solved; then the rotation of one shaft, representing the continuous increase of the independent variable, drives the rest of the machine in accordance with the equation. For fuller accounts of the machine and its mode of application, the reader is referred to the more detailed accounts which have been published.*

Since the differential analyser only handles directly ordinary differential equations, a partial differential equation has to be reduced (exactly or approximately) to one or more ordinary equations before the machine can be applied to it. In special cases, when the variables are separable, this can be done exactly, but in other cases it is necessary to resort to an approximation. A convenient approximation, and a means of correcting for the greater part of the error introduced by making this approximation, is explained in the text [cf. Section (3)]. As the application of the differential analyser to partial differential equations is an important extension of its range, and as the work described in this paper forms the first example of this application which has been made, it seems desirable to give a short account here of the way in which the solution of the equation was carried out.

As shown in the text, the equation whose solution is to be evaluated is [cf. Section (3)]

$$\frac{\partial^2}{\partial\xi^2}(\phi_1 + \phi_0) = \frac{2}{\delta\tau}(\phi_1 - \phi_0) - 2\beta e^{\frac{1}{2}(\phi_1 + \phi_0)} \quad . \quad (13)$$

where the initial temperature distribution, namely ϕ_0 as a function of ξ, is known, and the final temperature distribution after a time interval $\delta\tau$, namely ϕ_1 as a function of ξ, is to be found. The boundary conditions are

$$\phi = 0 \text{ at } \xi = 0, \ \frac{\partial\phi}{\partial\xi} = 0 \text{ at } \xi = 2 \quad . \quad . \quad (14)$$

The equation (13) can be set up on the differential analyser in several different ways. Fig. 9 shows a schematic diagram for what seems the simplest set-up; Bush's standard notation for the units of the machine is followed.* The actual set-up used was slightly different in details; the modification leading to the set-up shown in Fig. 9 was not noticed until after the completion of this work.

In setting an equation on the machine, it is often most convenient to consider it integrated once with respect to the independent variable. For example, (13) would be considered in the form

$$\frac{\partial}{\partial\xi}(\phi_1 + \phi_0) = \int\left[(2/\delta\tau)(\phi_1 - \phi_0) - 2\beta e^{\frac{1}{2}(\phi_1 + \phi_0)}\right]d\xi \quad (15)$$

In handling equations of this form, which arise from the replacement of a partial derivative by a finite difference, it seems likely that it will usually be most convenient to supply to the machine the information concerning the initial behaviour of the dependent variable in terms of the highest derivative occurring in this once-integrated form. This is certainly the case with the present equation, for a reason which will be explained in the following Section. Thus we supply $2\partial\phi_0/\partial\xi$, as a function of ξ, to the machine from the input table. The machine constructs $\partial(\phi_1 + \phi_0)/\partial\xi$ by evaluating the integral on the right-hand side of (15). It is necessary to record $2\partial\phi_1/\partial\xi$, which will serve as $2\partial\phi_0/\partial\xi$ for the next τ-interval, and also to construct $\partial(\phi_1 - \phi_0)/\partial\xi$, which must be integrated in order to provide the first term in the integrand in (15); these are obtained from $\partial(\phi_1 + \phi_0)/\partial\xi$ and the input $2\partial\phi_0/\partial\xi$ by adding units. The exponential $e^{\frac{1}{2}(\phi_1 + \phi_0)}$ is generated by integrator IV by solution of the auxiliary equation

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* See References (4), (8), (9), (11)

* See References (6), (9).

$$\frac{dz}{dy} = z \qquad \left[y = \tfrac{1}{2}(\phi_1 + \phi_0),\ z = \beta e^{y}\right].$$

(b) Procedure.

Equation (13) with boundary conditions (14) is a non-linear equation with one boundary condition to be satisfied at each end of the range of integration. In general, the machine solution of equations of this type can only be carried out by trial and error, since the process of integration must start from definite values of all relevant quantities at a single value of the independent variable. In the present case, the integration was carried out from $\xi = 0$ into the slab, using the known value $\phi_1 = 0$ at $\xi = 0$, and adjusting $(\partial\phi_1/\partial\xi)_{\xi=0}$ by trial and error until a solution was obtained satisfying the condition $\partial\phi_1/\partial\xi = 0$ at $\xi = 2$. The form of this boundary condition at the far end of the range of integration is one reason for taking $\partial\phi/\partial\xi$ as the function supplied to the machine as the information regarding the solution at the beginning of the time interval $\delta\tau$, and recorded as output. Also, the adjustment of $(\partial\phi_1/\partial\xi)_{\xi=0}$ so as to make the output curve go through the point $\partial\phi_1/\partial\xi = 0$ at $\xi = 2$, is both easier and more sensitive than the adjustment to make the curve of ϕ_1 become horizontal there.

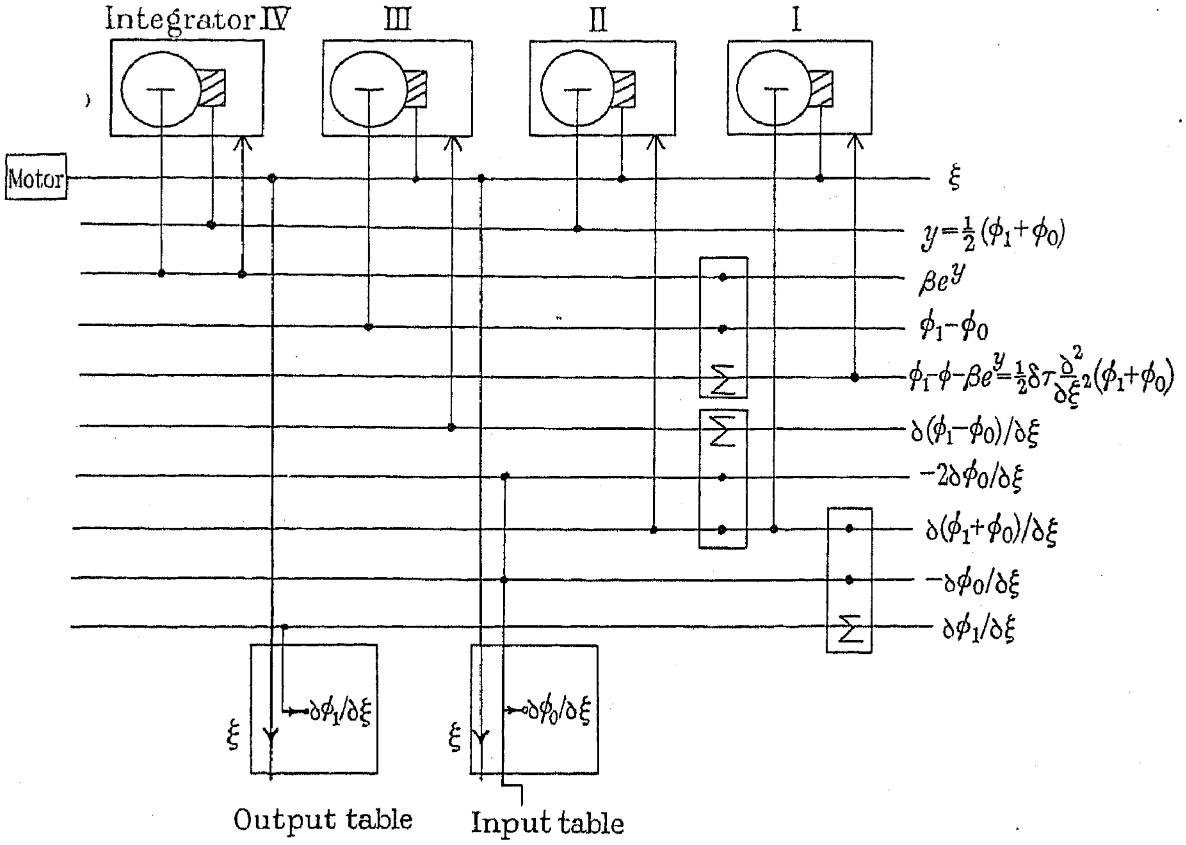
Integrator IV
III
II
I
Motor
ξ
$y=\frac{1}{2}(\phi_1+\phi_0)$
βe^{y}
$\phi_1-\phi_0$
$\phi_1-\phi-\beta e^{y}-\frac{1}{2}\delta\tau\frac{\partial^2}{\partial\xi^2}(\phi_1+\phi_0)$
$\partial(\phi_1-\phi_0)/\partial\xi$
$-2\partial\phi_0/\partial\xi$
$\partial(\phi_1+\phi_0)/\partial\xi$
$-\partial\phi_0/\partial\xi$
$\partial\phi_1/\partial\xi$
Σ
Σ
Σ
ξ
$\partial\phi_1/\partial\xi$
ξ
$\partial\phi_0/\partial\xi$
Output table
Input table

Fig. 9.—Schematic set-up diagram for differential analyser. (Scale factors and signs disregarded.)

Solutions with different values of $(\partial\phi_1/\partial\xi)_{\xi=0}$ diverge rather rapidly from one another as ξ increases, especially for the smaller values of $\delta\tau$; and instead of going back to $\xi = 0$ for each trial solution it seemed best to obtain two which bracketed the correct solution rather closely, to interpolate between these at some intermediate value of ξ, and to continue the integration from this point. This process was usually repeated at a later intermediate value of ξ. An example is shown in Fig. 10. Here curve A gives the temperature gradient through the slab at time $\tau = 2\frac{1}{4}$, and so forms the input curve for the step $\tau = 2\frac{1}{4}$ to $2\frac{3}{8}$; the lightly-drawn curves form a set of trial solutions with different starting values of* $12\partial\phi_1/\partial\xi$, the appropriate value being marked against each curve. The solutions for $12(\partial\phi_1/\partial\xi)_{\xi=0} = 21{\cdot}43$ and $21{\cdot}45$ are interpolated at* $1024\xi = 600$, and started from there, and those for $12(\partial\phi_1/\partial\xi)_{\xi=0} = 21{\cdot}44$ and $21{\cdot}445$ are similarly interpolated at $1024\xi = 1200$. The interpolation at the intermediate values of ξ is carried out on the readings of the integrator displacements; for example, for $12(\partial\phi_1/\partial\xi)_{\xi=0} = 21{\cdot}4$ and $21{\cdot}5$ the machine was stopped at $1024\xi = 600$ and all integrator displacements read; then the solution for $12(\partial\phi_1/\partial\xi)_{\xi=0} = 21{\cdot}43$ and $21{\cdot}45$ were started from here by linear interpolation between these values of the displacements. The heavy curve B is the final curve interpolated between the curves for the various trial solutions in such a way as to give $\partial\phi_1/\partial\xi = 0$ at $\xi = 2$; this then forms the input curve (corresponding to A) for the next time-interval, and so on. For the next time-interval only the final interpolated curve (corresponding to B) is shown, to avoid confusing the figure, and for the same reason the curves are drawn from different origins.

Using the special input table, originally designed for handling the equations of a system with a time-lag, it is possible to supply the input and record the output on the same sheet of paper (very much as shown in Fig. 10), and this is convenient as it enables the operator who is following the input curve also to see how the trial solution is behaving, so that as the machine is running he can judge whether this trial solution is likely to be a good approximation or if it should be stopped and a solution with a different initial value of $\partial\phi_1/\partial\xi$ tried.

As already explained in the paper on this general method of integrating partial differential equations,† there are two ways of applying the correction for finite length of τ-interval. We may either take two small intervals $\delta\tau = \Delta$ and one large one $\delta\tau = 2\Delta$ from τ_0 to $\tau_0 + 2\Delta$, use the corrected results at $\tau_0 + 2\Delta$, and continue from there in a similar way; or we may cover a range T by two independent integrations, one with a series of intervals Δ and the other with a series 2Δ, and correct the final results of these two separate integrations. The latter process has mainly been used in the present work, when any correction was required.

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* The factors 12 and 1024 appear here on account of the scales adopted in the machine set-up.

† See Reference (3), Sec. 3 (ii).

If graphs of the distribution of temperature through the slab at different times are required, it seems best to leave the construction of them until the end of the process of integration; they can then be drawn by using a subsidiary set-up of the machine to integrate the $\partial\phi/\partial\xi$ curves which have been used as input curves in the course of the solution of the equation.

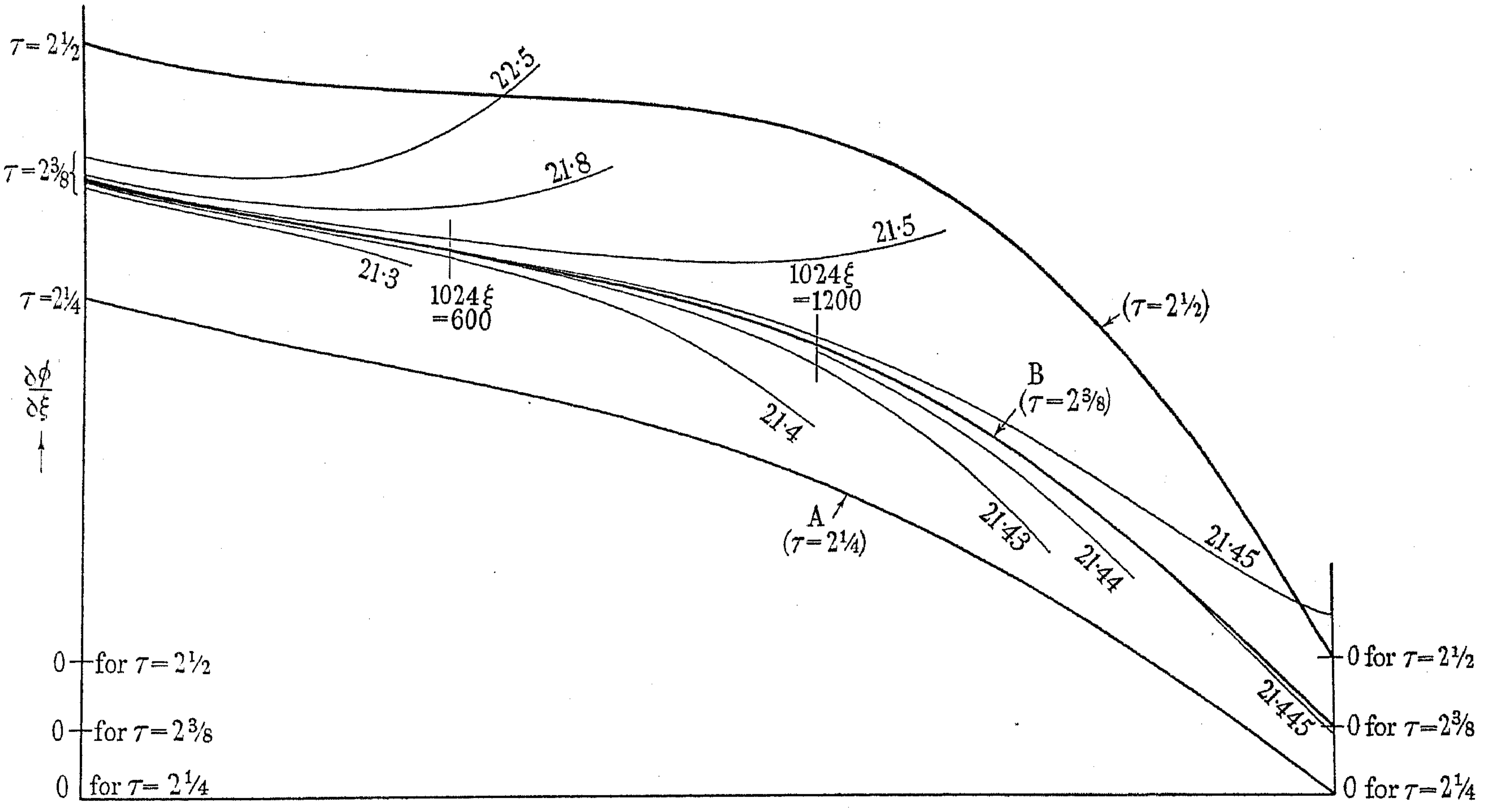

Fig. 10.—$\beta = \frac{1}{8}$. Curves of temperature gradient $\partial\phi/\partial\xi$ as functions of ξ at different times, to show the method of obtaining a solution of the equation satisfying the boundary conditions. Curve A, $\partial\phi/\partial\xi$ at $\tau = 2\frac{1}{4}$ (input curve for interval $\tau = 2\frac{1}{4}$ to $2\frac{3}{8}$). Curve B, $\partial\phi/\partial\xi$ at $\tau = 2\frac{3}{8}$ (interpolated from solutions, shown by thin curves, with different trial values of $12\partial\phi/\partial\xi$ at $\xi = 0$).

APPENDIX III

Starting the Integration

As mentioned in the paper, it is necessary to use an analytical solution in order to get away from the singularity at $\tau = 0$ before starting the machine solution. This can be done, since for small τ, ϕ does not differ greatly from zero and it may be possible to replace equation (4), to an adequate approximation, by

$$\frac{\partial\phi}{\partial\tau} = \frac{\partial^2\phi}{\partial\xi^2} + \beta \quad . \quad . \quad . \quad . \quad . \quad (16)$$

or by

$$\frac{\partial\phi}{\partial\tau} = \frac{\partial^2\phi}{\partial\xi^2} + \beta(1 + \phi) \quad . \quad . \quad . \quad . \quad (17)$$

for which formal solutions can be found in rapidly convergent series if not in finite terms. Solutions in Fourier series can easily be obtained,* but for small τ they are inconvenient for numerical evaluation as they are only slowly convergent, and it is more convenient to make use of another form of series, based on the use and interpretation of Heaviside operators.

For very small τ, ϕ will be small, and the temperature distribution near the one boundary $\xi = 0$ will not be appreciably affected by the presence of the other boundary, so that to an adequate approximation we can replace (4) by (16) and the boundary conditions (7) by

$$\phi = 0 \text{ at } \xi = 0,\ \partial\phi/\partial\xi \to 0 \text{ as } \xi \to \infty \quad . \quad (18)$$

Then writing $\quad p = q^2 = \partial/\partial\tau$

and solving (16), subject to the conditions (18), we have the solution in the operational form

$$\phi = \beta q^{-2}(1 - e^{-q\xi}) \quad . \quad . \quad . \quad (19)$$

Now it can be shown† that if $\chi_n(w)$ is the $(n + 1)$-fold repeated integral of $(-)^{n+1}(2/\sqrt{\pi})e^{-w^2}$, with the constants of integration so chosen that $\chi_n(\infty) = 0$, then the interpretation of $q^{-n}e^{-q\xi}$ is

$$q^{-n}e^{-q\xi} = (4\tau)^{n/2}\chi_n(\xi/2\tau^{\frac{1}{2}}) \quad . \quad . \quad . \quad (20)$$

so that the interpretation of (19) is

$$\phi = \beta\tau[1 - 4\chi_2(\xi/2\tau^{\frac{1}{2}})] \quad . \quad . \quad . \quad (21)$$

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* The Fourier series solution of (17) has been given by Goodlet, Edwards, and Perry [see Reference (1), Appendix III].

† See Reference (10), par. 3.

The functions $\chi_1(w)$ and $\chi_2(w)$ have been evaluated and tabulated,* and a recurrence formula given by which functions $\chi_n(w)$ with $n > 2$ can be calculated, for use in this and similar contexts.

If ϕ is still so small that (16) is an adequate approximation, but the slab is so thin that the temperature distribution is affected by the proximity of the two faces, so that the boundary conditions must be taken in the form (7), the operational solution is similarly

$$\phi = \beta q^{-2}\left[1 - \frac{\cosh q(2 - \xi)}{\cosh 2q}\right] \quad . \quad . \quad (22)$$

Expanding in negative exponentials and using (20) to interpret the resulting series, this gives

$$\phi = \beta\tau\Big[1 - 4\chi_2(\xi/2\tau^{\frac{1}{2}}) - 4\chi_2\{(4 - \xi)/2\tau^{\frac{1}{2}}\} + 4\chi_2\{(4 + \xi)/2\tau^{\frac{1}{2}}\} + \ldots\Big] \quad . \quad (23)$$

For small τ this is very rapidly convergent and is much simpler than the Fourier series for numerical evaluation, provided that a table of the function $\chi_2(w)$ is available. This solution (23) may be regarded as derived by the superposition of a number of solutions of the form (21), with different origins of ξ, in such a way that the result is symmetrical about $\xi = 2$ and gives $\phi = 0$ at $\xi = 0$.

The operational solution of (17) is more complicated but not unmanageable. With the boundary conditions (18) for an infinitely thick slab it gives†

$$\phi = \beta\tau\Big[1 - 4\chi_2(\xi/2\tau^{\frac{1}{2}})\Big] + (\beta\tau)^2\Big[\{1 - 4\chi_2(\xi/2\tau^{\frac{1}{2}})\} - \tfrac{1}{2}\{1 - 32\chi_4(\xi/2\tau^{\frac{1}{2}})\}\Big] + \ldots \quad (24)$$

and a solution satisfying the boundary conditions (7) for a finite slab can be built up by superposing solutions of this kind with arguments $\{(4m \pm \xi)/2\tau^{\frac{1}{2}}\}$, ($m$ taking integral values), in the same way as (23) for a finite slab is built up from the solution (21) for an infinite slab.

An alternative procedure is to work in terms of the difference of the solutions of (4) from that for a constant rate of generation of heat. If ϕ is the solution of (4) and Φ is the solution of (16) with the same boundary conditions, write

$$\phi = \Phi + \psi$$

then ψ satisfies the equation

$$\frac{\partial\psi}{\partial\tau} = \frac{\partial^2\psi}{\partial\xi^2} + \beta[e^{\Phi+\psi} - 1] \quad . \quad . \quad . \quad (25)$$

and if $e^{\psi} - 1$ can be neglected compared with 1 this equation can be replaced to an adequate approximation by

$$\frac{\partial\psi}{\partial\tau} = \frac{\partial^2\psi}{\partial\xi^2} + \beta[e^{\Phi} - 1] \quad . \quad . \quad . \quad (26)$$

which has the advantage of being linear, so that its solution can be written as the sum of a particular integral and a complementary function. Thus the trial-and-error process, referred to in Appendix II, for determining a solution satisfying the boundary conditions, is unnecessary in this case.

Using the solution (23) for Φ, (26) can be solved numerically by the method whose application to the main equation (4) has already been outlined in Section (3); or, better, a rough solution for ψ can be evaluated from (26) and then used in the exponential on the right-hand side of (25), following the iterative method suggested elsewhere.* For the case $\beta = \frac{1}{4}$, this method was used to obtain the temperature distribution at $\tau = \frac{1}{2}$, from which the machine integration was started.

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* See Reference (10).

† *Ibid.*

* See Reference (3), sec. 3 (i).

LONG-PERIOD AGEING TESTS ON SOLID-TYPE CABLES

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SUMMARY

For the assessment of quality of "solid" or "mass-impregnated" paper-insulated extra-high-voltage cables, no combination of simple tests has been found to approach in informative value an accelerated ageing test conducted at a medium over-voltage with severe cycles of conductor loading. The paper describes the technique employed by the authors in carrying out such tests and the methods used to correlate the results obtained with performance in actual service. The life-test histories of a number of experimental cables have been selected to illustrate a general discussion of the phenomena observed, and a relation between the over-voltage of the test and the life of the cable has been established. The paper reports a programme of work that has extended over at least 8 years, and it has proved possible to demonstrate by means of a family of curves the general trend of improvement over this period. The results obtained indicate that 60-kV solid-type cables are practicable and that the possibility of 132-kV solid-type cables meeting commercial requirements cannot be overlooked. Arising from the more uniform quality of impregnation that is achieved to-day, it is probable that a majority of the breakdowns now experienced on test are determined by inconsistencies in the make-up of the solid components of the cable. It is proposed to discuss in greater detail the influence of other factors in a further paper.

CONTENTS

Introduction.
(1) The Requirements of a Quality Test.
(2) Test Technique.
    (2.1) Test plant.
    (2.2) Arrangement of cables.
        (2.21) Cable types.
        (2.22) Layout of cable field.
        (2.23) Cable terminations.
        (2.24) Joints.
    (2.3) Testing methods.
        (2.31) Testing procedure.
        (2.32) Test criteria.
(3) Test Results.
    (3.1) General discussion.
    (3.2) Selected life-test histories.
    (3.3) Ageing characteristics.
        (3.31) The relation between voltage and life.
        (3.32) Stability during ageing.
        (3.33) Tests after ageing.
    (3.4) Discussion of results.
(4) Conclusions.
Acknowledgments.
References.
Appendix 1. Lapping Analysis.
Appendix 2. Visual Assessment of Deterioration.

INTRODUCTION

In the development of a cable suitable for extra-high-voltage transmission there have been four main methods of attack: (1) Oil-filled cable. (2) External gas-pressure cable. (3) Internal gas-pressure (or gas-filled) cable. (4) Cables of normal construction, commonly known as "solid" or "mass-impregnated" cables.

The devices incorporated in (1), (2), and (3) above, in order to overcome difficulties arising from oil or compound expansion during loading cycles, can only be justified for cases in which the limitations of the normal type of cable are such as to render the cable uneconomic or unsafe. It therefore appears to be desirable to establish what limitations of electrical stress, conductor temperature, etc., are inherently imposed on normal cables.

Some 8 years ago, after several years had been spent on a research dealing with oils, papers, and the general physics of cables, it was decided that a study of actual cables in service was vital to the development of really high-quality cable of normal type. The research referred to had resulted in the detailed design (including processing specifications) of a 3-core 30-kV‡ screened cable which has since, without any fundamental change, been manufactured in considerable quantity and has given extremely satisfactory service. Single-core cable, however, manufactured on identical lines, was somewhat inferior in performance. At 60 kV this difference became notable, although on the basis of standard acceptance tests there was little or nothing to choose between multi-conductor and single-conductor cables. It became evident, therefore, that some form of final check approximating to "trial in service" was necessary to ensure that unsatisfactory types of cable were not issued for commercial service.

Installation in the network of an operating company was obviously impracticable in view of the destructive nature of the test that was visualized, but it was considered feasible to design a testing plant to reproduce all the conditions under which cable operated and yet give the facilities which such a research requires. It was realized that the method would be slow to produce results and expensive to carry out, but its value has been amply proved by the practical results achieved.

Solid-core 60-kV single-core cable was originally selected as the basic type, partly because of the phenomenon referred to above and partly because it was felt that this type of cable would always be able to compete on an economic basis with the other forms of cable proposed for work at this voltage, provided it could be

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* Standard Telephones and Cables Ltd.
† Enfield Cable Works Ltd. (formerly with Standard Telephones and Cables Ltd.).

‡ In accordance with established custom, the voltage-ratings of the cables referred to in this paper are expressed in terms of the 3-phase system to which they are applicable. Since testing has been restricted to screened cables, it has been considered less ambiguous, although productive perhaps of less impressive figures, to express testing voltages throughout as the single-phase voltage from conductor to earth.

established that it was capable of operating at a conductor temperature not less than 65° C. for a life not notably less than that of solid cables operating at lower voltages. Work on solid-type 60-kV cables provided an excellent basis not only for effecting improvements in the performance of similar cables working at 30 kV and lower voltages but also for extending the investigation to 132 kV if the results justified this course.

It has been found expedient in some cases to carry out tests on 10-kV and 30-kV cables, and more recently the tests have been extended, as envisaged earlier, to 132-kV solid-type cables.

All experimental cables have been processed in the factory under closely observed but essentially practical conditions, and their characteristics have been watched carefully throughout their useful life. Tests have also been carried out on standard cables consisting of additional lengths made up with commercial orders and selected from such orders after consideration of the acceptance-test results and the process-test results. These observations have been supplemented from time to time by tests on lengths of cable removed from actual service, and these have formed a basis of comparison for the artificially aged cable. In certain cases it has been found possible to make ageing tests on these returned lengths; the results of these examinations and tests have all contributed to the analysis of the phenomena associated with impregnated paper cables.

This paper gives a preliminary survey of the work carried out to date, in the hope that the results so far obtained will assist in allaying certain fears which obviously influence cable users not only with regard to the use of solid-type cables for working voltages of 60 kV and upwards but also with regard to the security of networks already installed for operating voltages of less than 60 kV.

Further work is obviously necessary before complete elimination of solid-type cable deterioration can be achieved and also before the ideal acceptance test can be evolved. The present paper, however, gives some indication of the fundamental nature of these problems, whence, it is hoped, rapid progress can be made.

(1) THE REQUIREMENTS OF A QUALITY TEST

Before embarking on a series of expensive and somewhat tedious tests of the type described in this paper a study was naturally made to determine whether or not it was possible to achieve the same end in a shorter period of time and at less cost.

It was known that condensers having an insulation of impregnated paper could give excellent service performance at stress values of the order of 12–15 kV per mm. Solid-type cables, however, appeared to enter the danger zone when stresses of 4 kV per mm. were exceeded. After making due allowance for the greater difficulties presented by the drying and impregnation of cables it was obvious that the main difference in performance between condensers and cables was the fact that cables had to withstand temperature cycles due to fluctuating loading. Stability or "type" tests, i.e. the checking of power factor before and after a heat cycle, indicated most clearly that in order to preserve a low ionization factor the maximum temperature of the conductor must be limited to a safe value. One objection at that time to the type test was the fact that it was not precisely known how to relate cables of differing basic power-factor and differing ionization factor in a bulk order to the one or two selected cables tested for stability. This problem, incidentally, has been simplified during the intervening years by a very considerable improvement in the uniformity of cable production, so that the stability test is now a more representative guide to the performance of the bulk order.

The carrying-out of the stability test on a drum was common practice—the controversy regarding oven heating versus heating by application of load will be remembered—and certain experiments appeared to show that by making adjustments to the cable design, and controlling the conditions of the test, stability could be maintained even though temperatures of 95° C. were attained (the usual service limit at that time was 45° C. for the class of cables under discussion). It therefore appeared to be necessary to standardize conditions for such tests by installing the cables in a manner corresponding to service conditions.

About this time attention was being drawn by published researches elsewhere to the various forms of deterioration which become evident during the service life of cables. These phenomena appeared worthy of study not only in cables in service, but also in cables undergoing some form of accelerated ageing test under controlled conditions. It will be seen later that tests made on cables subsequent to ageing are often more informative than the overall tests taken during ageing. The other tests presented in specifications were dismissed as being non-informative except when applied in conjunction with some form of service ageing. Ionization factor could be measured before, during, and after ageing tests. Breakdown value, particularly with reference to time, would be much more informative if it were taken before and after ageing tests. Voltage application for 15 to 30 minutes ("pressure test") has always been accepted as a detector of serious mechanical defects rather than as a criterion of service quality. There appeared to be no alternative but long-period ageing tests under conditions approximating to service conditions.

This point having been decided, there remained the problem of fixing the conditions of the test so that maximum information would be obtained. Elsewhere accelerated ageing tests were being discussed, and these have since developed in other laboratories into standardized tests in which results are obtained rapidly by application of voltages of the order of 2 to 3 times working voltage in conjunction with loading cycles, in some cases producing temperatures of the order of 100° C. It cannot be denied that such tests have had a profound effect in raising the standard of quality, but it may also be claimed that they impose certain restrictions on cable development. If the designed working stress of a cable is 3·5 kV per mm. it may be possible for the cable to withstand an accelerated ageing test of the order of 7 to 10 kV per mm. It by no means follows, however, that because a cable fails to withstand an accelerated ageing test at, say, 12 kV per mm. the cable cannot work safely at 6·5 kV per mm. The closer to its safe value of stress the cable is worked the more economic its use, but the smaller the ratio of test voltage to working voltage. The accelerated ageing test of the type discussed tends to force the cable maker to design against quality tests rather than against service performance.

The fundamental development question which has to be answered is how to arrive at the most economic design of cable for the transmission of given bulk units of energy. The economics will depend on:—

(*a*) The stress at which the cable can be worked; this determines the thickness of insulation, the cable dimensions, and therefore to a considerable extent the cost of the cable.

(*b*) The maximum temperature at which the conductor may be worked; this determines the conductor section and the cable cost so far as it is affected thereby.

(*c*) The basic value of dielectric loss in the insulation; this affects annual costs.

(*d*) The deterioration factors of the cable, which in the limit determine effective life and thereby fix the depreciation costs of the cable.

Observation of the behaviour of cables in service will of itself contribute little to our knowledge of these factors unless risks are taken by the operating companies by raising the stress value or the temperature until trouble is experienced. This is in general commercially impracticable. The alternative is the determination of maximum safe values by long-period tests in which the following conditions are specified:—

(*a*) The stress value chosen is one which gives some reasonable expectation of long life. In general, tests must be made simultaneously at several stress values in order to obtain a stress/life curve which will indicate the maximum safe value. (The range selected was from 5 to 7·5 kV per mm.)

(*b*) Selection of a temperature sufficiently high to guarantee economic performance of the cable in service but sufficiently low to ensure reasonable expectation of success being obtained by improvement in cable design and quality. (The temperature selected was 75° C., as compared with the 45° C. which was then common practice but in contrast with the 95° C. obtained on stability tests.)

(*c*) Judgment of results obtained on the basis of breakdowns and cable deterioration.

(*d*) Correlation of results with service performance by introducing into service, as the tests progressed, cables working at stresses indicated by the tests but higher in value than those prevailing in normal cables. Further correlation by removing lengths of cable from service and determining their state of deterioration not only by voltage tests, dielectric tests, etc., but also by submitting them to long-period life tests and contrasting their performance with that of virgin cables similarly treated.

The value of tests of this nature will be discussed again later in this paper when the test technique has been described and some of the results examined.

(2) TEST TECHNIQUE

(2.1) Test Plant

Three distinct sets covering the complete range of high-voltage cable production are in use, and they are briefly described below in the order in which they have been introduced.

Interest in the effect of combined current loading and over-voltage may be said to date, in the practice of the manufacturing organization with which the authors are associated, from 1924, when three single-phase loading transformers of 25 kVA capacity and insulated for 150 kV were included in the specification for a 450-kV set installed for routine and experimental testing.*

The potential is set up by three 150-kV transformers which can be connected in parallel or in series, or can be used as a 3-phase system. As the use of this set for production purposes increased and the requirements imposed by developments in accelerated ageing tests came to be recognized, its functions in this latter respect were superseded by the sets described below. A general schematic arrangement showing this type of test set is illustrated in Fig. 1.

(*a*) Plant No. 1 comprises a motor-generator set feeding a 250-kVA potential transformer rated at 90 000/440 volts and a 25-kVA loading transformer insulated for 90 kV. Voltage control is effected in both cases on the appropriate alternator field by separate exciters driven in tandem from the same motor. The generator feeding the potential transformer provides on open circuit a sine wave of voltage of less than 2 % harmonic content. The high-voltage windings of both transformers are completely screened. The screens are normally earthed, but provision is made for their insulation from earth to permit measurements of power factor on earthed cable.

At a later stage the plant layout was modified to permit continuous operation directly from the supply mains. Moving-coil regulators were employed for this alternative connection, and the motor-generator set with its low efficiency and higher maintenance charges is normally reserved for power-factor measurements.

(*b*) No. 2 Set has been employed for miscellaneous tests in the range of 10- to 30-kV cables, and is composed of two independent mains-operated units suitable for indoor use. A 50-kV 10-kVA transformer provides the testing voltage, which is regulated by means of a multi-tap auto-transformer on the primary side. For current loading a combination of two transformers is used: a 1 : 1 ratio 10-kVA transformer, wound for 230 volts with the secondary insulated for 30 kV, is used in conjunction with one of a series of low-voltage step-down transformers which find a general use in laboratory work. This second transformer is mounted on a porcelain insulator, and one pole of the primary and secondary windings is connected to its frame and to the potential transformer. This arrangement has been adopted to give the flexibility required for varied lengths of loop and cable types ranging from 10-kV "rural" to 0·25-sq. in. 30-kV cables.

(*c*) No. 3 Set is intended to cover the range of cable of voltages higher than 60 kV for 90- to 150-kV single-phase testing. Voltage is supplied by a 500-kVA transformer of 150/6 kV, which is controlled by a motor-operated moving-coil regulator from the 6-kV supply. A tertiary winding gives an accurate indication of the test voltage. The circuit-breaker is fitted with the normal trip and no-volt coils, energized respectively by over-voltage and overload relays and interlock circuits. A 25-kVA trans-

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* See Reference (1).

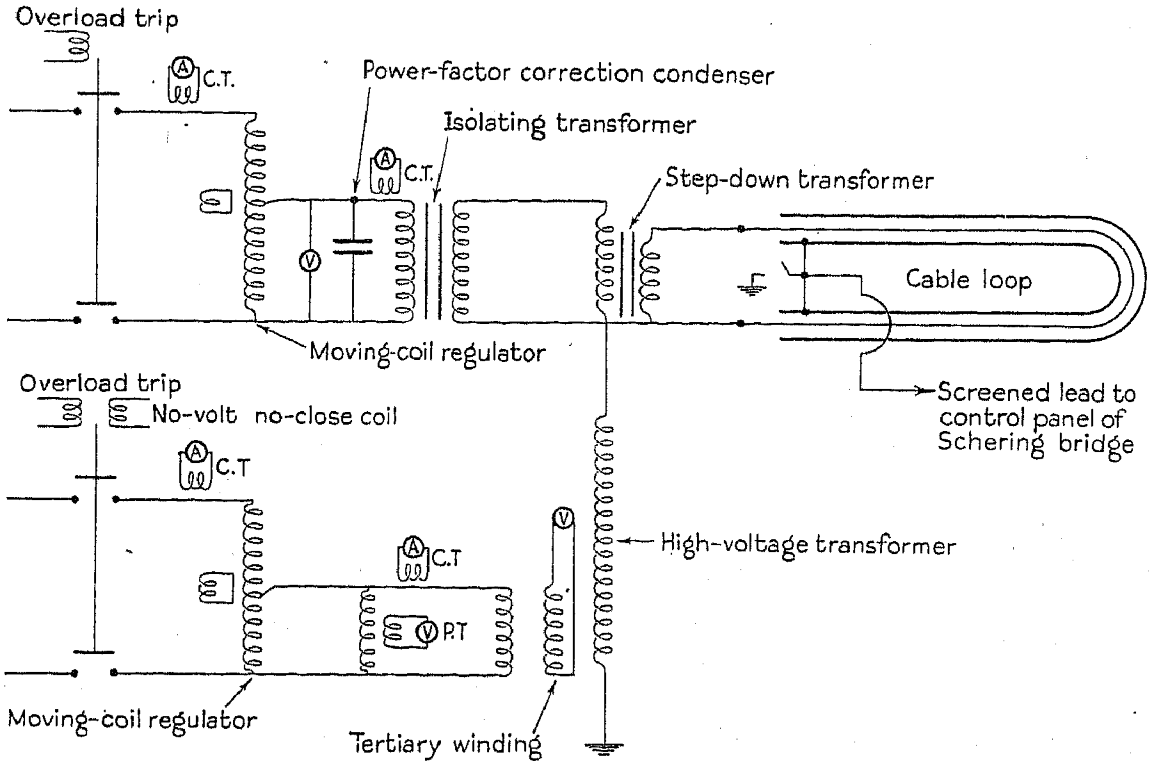

Fig. 1.—Schematic arrangement of phantom loading of cables.

former, 415/125/62·5 volts, with the secondary insulated for 150 kV, provides the circulating current for the cable loop. The load is in this case also controlled by means of a moving-coil regulator. A condenser of some 400 μF capacitance is connected across the secondary of the regulator to correct for the reactance of the cable loop on test. This achieves the double effect of improving the power factor of the mains load and reducing at the same time the rating of the control apparatus required.

(2.2) Arrangement of Cables

(2.21) Cable types.

The main body of experimental work has been carried out on 60-kV cable, for it was this class of cable which demonstrated most marked deficiencies at the time that this programme was initiated. However, the range of cable both in voltage and in type is most comprehensive, as the list of selected cables in Section (3.2) shows. Reference may be made here to three special types which have played a large part in this testing programme.

(*a*) *S.R. cable.*—In an endeavour to harness the capillary forces of the paper fibres for the purpose of maintaining the dielectric completely filled with compound, it is necessary to hold the compound, which on heating has exuded from the paper matrix, in close proximity to it.* For this purpose space is provided by building up the conductor with perforated metallized paper, which is applied interlocking and with contacting metallized faces. In this way the large spaces, which on cooling are denuded of compound, are screened from electrical stress. It is an essential feature of this design that the dielectric is graded so that the parts most severely stressed are formed of paper with the most highly absorptive properties.

(*b*) *Intersheath cables.*—A second phase in the development of special cable types was the extension of the capillary theory to its logical conclusion by inserting a " reservoir " in the centre of the impregnated dielectric, similar to that employed in cables of the previous class. Owing to the enhanced electrical stresses involved and in view of the revelation of other factors, such as non-uniformity and poor impregnation, which obviously had a predominating influence on cable failure, this design was discarded at a later stage. It may be significant, however, that on a stress basis this type of reservoir cable has behaved as satisfactorily as have the more normal types.

(*c*) *Multi-conductor* (*M.C.*) *cable.*—Within the last few years another type of intersheath cable (Fig. 2) has been investigated in which the geometric form of the dielectric has been so disposed as to equalize to a marked extent the non-uniform radial distribution of electrical stress. The increase in radial stress in the vicinity of the conductor of the normal cable arises from the restricted cross-section of the dielectric at those parts. In the M.C. design this stress is relieved by splitting the conductor into a number of parts and by providing each with a concentric screen. These screens are connected to one another throughout the length of the cable, so that the partial capacitances between each conductor and screen are connected in parallel and the radial stresses are thereby reduced. For the case in which the conductor is split into three parts, the maximum possible stress reduction in comparison with the normal cable designed

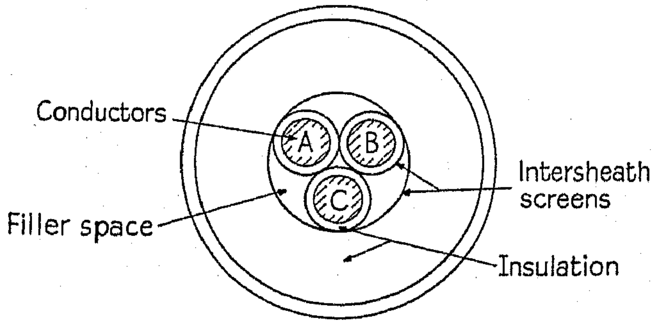

Fig. 2.—Arrangement of M.C. (single-phase) cable.

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* See Reference (2).

for minimum stress is 10 %, and this is attained as the diametral ratio of cable and normal conductor approaches a value of 4. Whilst the reduction in maximum stress is thus distinctly limited, it is interesting to observe that, in relation to the established stress/life curves, this design has behaved extremely well, so that it is possible that other factors are able to exert a favourable influence on its impregnation or subsequent performance.

(2.22) Layout of cable field.

It was felt that the outdoor installation of the test cables, which was prompted by economic considerations, is particularly conducive to severe test conditions and therefore acceptable. In one of the test locations (at Hendon) a field of adequate size in the vicinity of the laboratory was available and the testing transformers could be located at one extremity. In the second field laboratory (at Woolwich) shortage of space dictated the use of a long flat roof which was conveniently situated. The high-voltage equipment was located on the ground level at some distance from the test field, and whilst the use of twin overhead conductors mounted upon stack-type porcelain insulators proved very satisfactory from a technical point of view, these connections were replaced some years ago by oil-filled cable lines of special design.

With regard to the installation of the test cables themselves, three methods have been adopted:—

(*a*) *Cables mounted on racks.*—Being exposed to the elements, the cables have proved too sensitive to atmospheric conditions to permit a reasonable control of the conditions of test. It was also felt that the low thermal resistance external to the sheath imposed undesirable features from the point of view of thermal gradient. Nevertheless, this arrangement has provided a considerable amount of interesting data upon the longitudinal migration of compound induced by the operation of sun and shade upon adjacent parts of the cable.

(*b*) *Cables buried in the ground.*—Whilst this method reproduces practical conditions, it has many disadvantages from the testing point of view. Sheath insulation was not considered practicable at the time that this method was in use, so that the measurements taken with sheath earthed were limited to tests on entire cable loops. Furthermore, the thermal capacity of the ground tends to maintain the ambient temperature at too high a level to permit the wide diurnal range of temperature which was considered desirable for an ageing test, and thermal records taken by means of thermocouples were necessarily restricted. It was considered desirable that cables should be tested right down to 0° C. on occasion. Finally, it may be noted that the method is expensive in installation and rules out the possibility of close observation of the behaviour of the cable.

(*c*) *Cables in troughs.*—This arrangement has been found to give the best compromise in regard to expense and convenience in testing. The troughs may be used with or without sand filling, and should be covered with tiles as a protection against the direct rays of the sun.

To attain reasonable accuracy of power-factor and capacitance measurement, a sheath insulation from earth of better than 10 000 ohms has been specified. With cables supported upon racks, the insulation of the wooden posts permits this figure to be achieved in all but the most adverse conditions. In the case where the cable is installed in troughs it is difficult to maintain an adequate figure, especially when the trough is for thermal reasons filled with sand, because it retains the moisture which filters in during rainy weather. Bearing this in mind, a number of the later experimental cables have been covered with Pernax over the lead. The results obtained have satisfied all expectations, and reliable measurements can be obtained over prolonged periods provided that due precautions are taken at the ends of the test length.

(2.23) Cable terminations.

The cables are terminated in porcelain end-bells, and a number of such end bells are mounted in an enclosed area into which the high-voltage supply is introduced.

In the early experiments the test cables were taken directly into end bells. This led to many extraneous disturbances which interfered with the examination of cable behaviour. End bells of that period were liable to admit air and moisture, so that electrical losses and breakdowns due to these effects tended to confuse the issue. Furthermore, migration of oil from the bell occurred, while " gassing " phenomena were sometimes induced as an after-effect. All these experiences were valuable from a research point of view since they provided first-hand information relating to well-defined conditions on troubles likely to be experienced with terminations in service.

As a result, tail cables, usually similar to that under test but sometimes having a higher factor of safety, were introduced. Barrier joints were formed between the tail cables and the cable under test so as to eliminate oil migration. End bells could in this way be studied without interference with the main cable test programme, except in so far as actual breakdown occurred.

Experience over a number of years has shown that the success of a termination under service conditions depends to a very great extent upon the quality of the cable which is terminated. The introduction of condenser cones some years ago* effected the complete elimination of end-bell trouble at the test voltages then obtaining, and the continued development of termination design and process methods has permitted the adoption of a standard type of 30-kV porcelain for continuous use at 60 kV (single-phase) with complete success. More frequent cleaning than could be tolerated in service conditions is of course necessary, but this may readily be fitted in with the testing programme. The employment of porcelains of minimum size and weight is an important consideration in the prosecution of an intensive testing programme of this nature.

(2.24) Joints.

The object of these tests is to obtain a criterion of performance under practical service conditions, but since many considerations limited the test sections to lengths of the order of 50 yards it was necessary to devise methods to simulate the conditions obtaining in long lengths corresponding to those of normal construction. For this purpose stop-joints are required, preferably of a type without reservoir capacity of compound. The development of the Styrene joint† met this demand, and since the dimensions of the joint can be made but little larger than that of the cable, it has been universally adopted in these tests, except where it has been expressly desired to obtain information on a particular design of joint.

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* See References (3) and (4).

† *Ibid.*, (5).

For convenience in operation it was required to include a number of test sections within a cable loop, and this calls for isolation of each individual sheath to permit power-factor measurements on each. For this purpose a bolted type of insulator has been used in which two heavy brass flanges are separated by an annular bakelite ring. The metallic screen is broken in the neighbourhood of the joint and then replaced on the one side so as to overlap the other and yet remain insulated from it. At a later stage it was found desirable to isolate each joint entirely from the test length. In this case the break in the metallized screen was made on either side of the joint and the joint connection was brought out in the centre, or through a filling plug as shown in Fig. 3.

The leads from the sheaths to the Schering bridge are completely screened, but since severe voltage surges are liable to occur in them in the case of a cable fault, short-circuiting links are placed on either side of the bakelite ring so as to reduce the impedance of the earth-return circuit to a minimum. In spite of these links the authors have experienced some trouble due to the failure of these insulating rings. A similar problem exists in service conditions where an attempt is made to reduce sheath circulating-current losses by means of cross bonding or the like.

(2.3) Testing Methods

(2.31) Testing procedure.

The basis of all accelerated ageing tests is the application of " phantom " loading to a cable loop so that the separate impression of over-voltage and current does not require the large input of power involved in service operation. The voltage is adjusted to such a figure as to limit the maximum stress to a value which will effect a deterioration process at a reasonable rate without inducing breakdown in a manner inconsistent with observed conditions pertaining to service. In practice the stress limits the authors have observed range from 5 to 8 kV per mm., and it has been found that these limits have in the past covered testing times from about 10 to more than 300 days.

In most cases a conductor section of 0·2 sq. in. has been standardized as being the smallest practical size for high-voltage working, although in a few cases it has been found convenient to vary this somewhat. Maximum conductor temperatures are permitted to fluctuate with the prevailing weather conditions, but the current is adjusted periodically to give a maximum of approximately 75° C. As a consequence, maximum values of 80° C. are sometimes obtained in summer, but in winter it is difficult to maintain the desired limit.

A value of 350–400 amp. is required to obtain the requisite heating on a 0·2-sq. in. conductor, and it is necessary to dispose the test loop so that the " go " and " return " lines enclose an area of minimum extent in order to keep the induced sheath voltages low. In operation the sheaths are short-circuited at the ends and the resultant sheath circulating current adds an appreciable quota to the heating. This is advantageous because

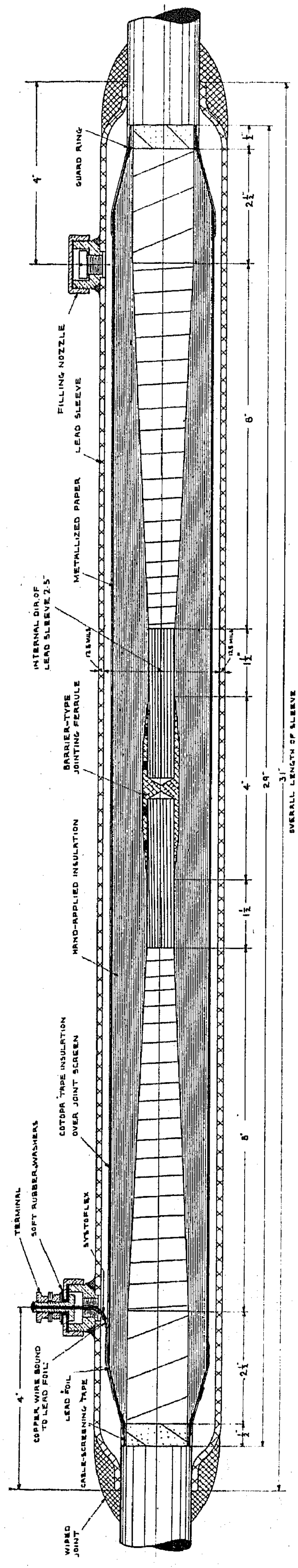

Fig. 3.—60-kV screened Styrene joint for pressure-type cable: general arrangement.

it increases the maximum sheath temperature, which tends to be low in comparison with buried cable on account of the low thermal resistance external to the sheath. The effect is of course automatically included in our records of operating temperature.

These temperature records are based on a continuous observation of the sheath temperature by means of thermocouples. To achieve adequate sensitivity with a robust type of recording instrument a number of junctions in series is employed. The requirements of electrical loss measurements prevent the intimate contact of couple and sheath, and care must be taken to ensure that an accurate record is obtained. The cold junctions are installed in a Dewar flask, and, where possible, buried in the ground. In other cases there is used an elaborate multi-walled container involving the maintenance of inner chambers of high thermal capacity within lagging of high thermal resistance. Iron-wire thermal indicators placed within the flask with the cold junctions have demonstrated that diurnal variations have been eliminated successfully, although seasonal variations still exist. Copper temperatures are calculated from the observed sheath temperature by the assumption of a figure for the thermal resistance of the cable, and the results so obtained are checked from time to time by actual measurements of copper resistance taken on the loop by means of a Kelvin bridge.

Load is normally applied during the day for 8 hours so that the final temperature for the particular current loading will be attained. Overnight the small thermal capacity of the cable lagging ensures that the cable closely approaches air temperature, and records below zero Centigrade occur frequently in winter months. Continuous records of voltage, load current, and sheath temperature, are taken.

Tests of capacitance and power factor are taken periodically by means of a Schering bridge, at intervals determined by experience of the manner in which these characteristics are varying. A capacitor filled with nitrogen at a pressure of 200 lb. per sq. in. permits power-factor measurements up to voltages of 150 kV. The usual precautions apply in attempting to measure the power factor of relatively small capacitances. The capacitance interlinkages of the various test leads are previously determined by means of a " capacitance and conductance " bridge, so that the appropriate corrections are accurately determined. The required condition of adequate screening of the cable sheath from external fields set up by the high-voltage conductor is easily met since the end bells are normally located some distance away and screened by an expanded-metal cage. Most important is the effect of leakage resistance of the sheath to earth external to the measuring bridge. This modifies the value of the capacitance as measured and also leads to inaccurate power-factor values which demonstrate a falling characteristic when plotted to a base of test voltage.

Normally the cables are run at constant voltage until breakdown occurs. The fault is then removed for inspection, and the examination extended to small samples of cable adjacent to the failure. Provided that the remaining test-length is of adequate size, the cable is then re-jointed and put back into service. It is unusual for a test to be carried on beyond a second failure. When a second breakdown occurs, the cable is cut up into convenient lengths, samples being taken at regular intervals and examined concurrently to establish any variations in the cable make-up. Tests carried out on these lengths, viewed collectively, will supplement the information provided by the cable during its test life and will enable an estimate to be made as to the uniformity of the cable.

(2.32) Test criteria.

The most important criterion in judging the performance of a cable must obviously be its span of life relative to the voltage at which it was tested. But to appreciate its significance it is important to establish the immediate cause of the breakdown, and this may be done by a careful visual examination of the failure and by consideration of the characteristics of the remainder of the test length. The variation of capacitance and power factor during life will, in the case of a well-impregnated cable, indicate the course of the physical changes which the cable is in the process of experiencing.

Visual examination of a number of samples can establish the radial and longitudinal variations in the cable from the point of view both of physical formation and of deterioration. The former will be based principally upon the appearance of the lapping: for the latter the authors have used a " visual deterioration factor " based on a series of values given in Appendix 2. Values have been allotted to the appearance of a cable paper based on the degree of waxing: striking an average for a complete cross-section gives a value which usually correlates well with other criteria given below. The shortcomings of this method are obvious: the personal factor is pronounced, and the assessment cannot allow for lack of local uniformity. Furthermore, the appearance of the tape changes with time as fresh oil oozes from the finer pores of the paper. When the examination of a number of samples is carried out simultaneously, however, fairly reliable comparative figures are obtained: for cable made of similar materials they do provide a qualitative measure which stands for all time. The magenta test of Robinson* has been used profitably in these examinations.

Power factor/voltage curves of different lengths of cable will determine the distribution of basic power-factor and ionization along the cable length; the variation of capacitance with voltage is bound up with the phenomenon of ionization. An important characteristic is the variation of power factor with temperature, and when the longitudinal distribution is correlated with a number of radial power-factor curves the origin of any observed deterioration will often be exposed.

Short-time breakdown tests on the individual lengths may be carried out by testing with either direct or alternating voltages: in the latter case the breakdown voltage/time relation will be very different from that of new cable. The level of electric strength gives a good estimate of the importance of the deterioration that has occurred, and it may be correlated with the radial distribution of strength as determined by tests on individual tapes.

* See Reference (6).

(3) TEST RESULTS

(3.1) General Discussion

In noting some of the observations that have been made during the course of these accelerated ageing tests, two points must be borne in mind. In the first place, the cables that have been placed under test within the past 8 years have demonstrated a steady improvement along the lines developed in another section of this paper, so that their behaviour on test has tended to alter accordingly: at the same time it has been necessary to increase the severity of the tests in order to arrive at some definite conclusion in regard to cable quality within a reasonable time. Secondly, it may be noted that the technique of testing methods has undergone steady development during this time, with the consequence that the earlier information is relatively unreliable and less complete.

There is a further difficulty in the reporting of an extended research programme which is concerned with developments in manufacturing methods, in that many of the test lengths were devoted to some specific research so that in some cases tests were discontinued as soon as their purpose had been served. No set programme is feasible over an extended period of time.

The experience which is drawn upon in this report is based upon the intimate testing of not less than 14 000 yards of cable, all of which was designed specifically for experimental work. From this amount of cable more than 60 individual test-lengths have been subjected to the authors' life-testing procedure, the remainder being subjected to the various corroboratory tests which are fundamental to any extensive cable-research programme. In addition, a number of lengths have been taken from time to time from normal productions or removed from actual installations after a period of service and incorporated in the testing programme.

It would serve little purpose to tabulate in detail the individual life history of each cable length, and furthermore it would inevitably confuse the issue. It is therefore proposed to present the test history of some half-dozen representative lengths which cover the range of the cable types investigated. These will serve to indicate quantitatively the order of the various effects quoted, with the observation that they are typical of the results obtained and do not represent an unusual or extraordinary performance. In every case known defects are present in the cable as tested. Reference will be made in the text to further individual cables wherever experimental evidence in support of some point is felt to be desirable.

It may be mentioned that the physical characteristics of these cables have been compared from time to time with other samples both of British and of foreign manufacture, so that the range of differences which can exist in comparison with normal practice is well appreciated.

Of the specific tests quoted in the following section it may be noted that, except where otherwise stated, power-factor tests on installed cable were invariably carried out after resting overnight without transmitting load-current, so that the cables might be expected to have attained atmospheric temperature. The power factor at zero voltage has been termed the " basic power-factor," and in practice this is based upon a value obtained at about 25 % of the rated operating voltage. The " ionization factor " as used hereafter may be defined as the increase in power factor for any stated voltage above the basic value. A voltage of approximately twice operating voltage has usually been adopted, but it is believed that its significance must be judged in relation to the previous testing voltage of the cable rather than any absolute value of stress.

(3.2) Selected Life-Test Histories*

(3.21) 10-kV, 0·05-sq. in. 3-core sector " H "-type cable (No. EC.62/1).

This cable represents a type proposed for rural lines in which the stresses adopted for e.h.t. working are applied to a cable of this rating operating within a limited temperature range. The insulation thickness is accordingly 100 mils and the temperature-rise for the conductor under normal conditions of full load (1 500 kVA) is of the order of 13 deg. C. In this particular experimental cable different paper types were employed for the individual cores, but these have caused only minor variations in the characteristics of the cable.

The cable was tank-impregnated in the way normally adopted at that time, and no unusual precautions were taken in its manufacture. Of the production length a portion was consumed in establishing the breakdown voltage/time curve; the asymptotic breakdown voltage proved to be approximately 28 kV to earth. The remainder, some 60 yards in length, was subjected to an accelerated ageing test at nearly 60 % over-voltage. The cable was laid in a bifilar loop on the laboratory floor, with Styrene joints towards each end. The cable ends were left open, the three cores being inserted in an 8-in. condenser cone filled with special plastic compound. The three insulated cores project beyond the cone and are normally at the same line potential; each single-phase end is, however, capable of withstanding a testing voltage of 15 kV with the other cores earthed, for power-factor measurements. The cable layout adopted involved a severe inverted vertical loop rising to a height of about 12 ft.

Fig. 4 shows graphically the course of the ageing test, which was conducted at a voltage of 10 kV to earth. Single-phase loading current was circulated through the cores, which were connected in series. The average range of temperature at 2-day intervals is plotted for the duration of the test. The variation of average power-factor and ionization is also shown.

The test was concluded without any electrical trouble after 354·4 days of voltage. The two joints were isolated with a suitable length of tail cable and the remainder divided into six sections of approximately equal length. The joints were tested with direct current, and the average breakdown voltage was 166 kV.

Four of the lengths were placed in a cable oven and the power factor/voltage curves for a number of temperatures (see Fig. 5) were obtained. The power factors in the case of the red phase are plotted logarithmically to a base of temperature in Fig. 6, whilst the trend of power factor in relation to the original cable-length is indicated in Fig. 7 for three temperatures. Only minor differences from these results are to be noted in the case of the other phases, due to the employment of different paper types.

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* In the coding adopted for the cables described in this paper, each design of experimental cable (E.C.) is allotted a number: a second number, separated from the first by a stroke, is used to refer to the particular length manufactured to this design. Divisions of the length subjected to test are denoted by a letter: subdivisions effected after the main test are indicated by a further series of numbers which mark the sequence points of reference. Thus " EC.58/1a " refers to a section of the first cable-length manufactured to the design of experimental cable number 58.

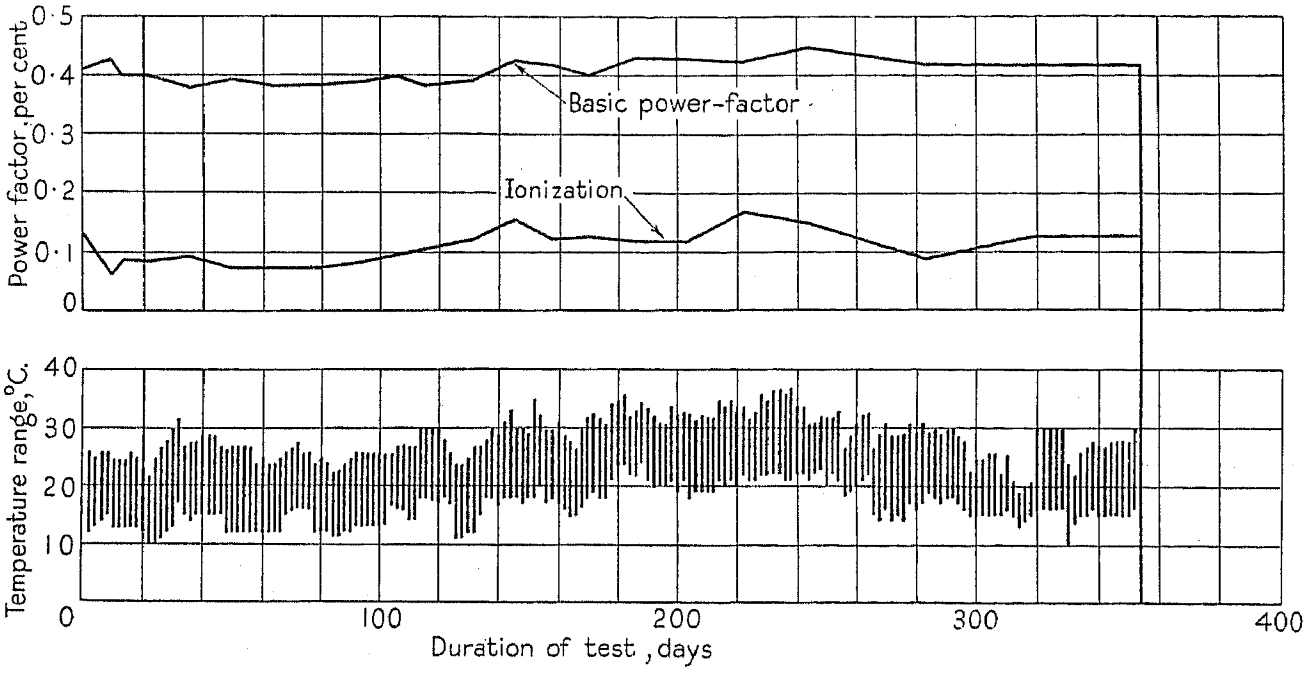

Fig. 4.—Life-test history of Cable No. EC.62/1.

It is obvious that a deterioration, which assumes severe proportions at 75° C. and higher, originates at the cable ends and penetrates almost to the cable centre. It is assumed that this loss is caused by compound oxidation due to the entry of air into the filler spaces. The severity of the effect arises from the open 3-core construction and the appreciable contraction of compound in a long cable-length after lead sheathing.

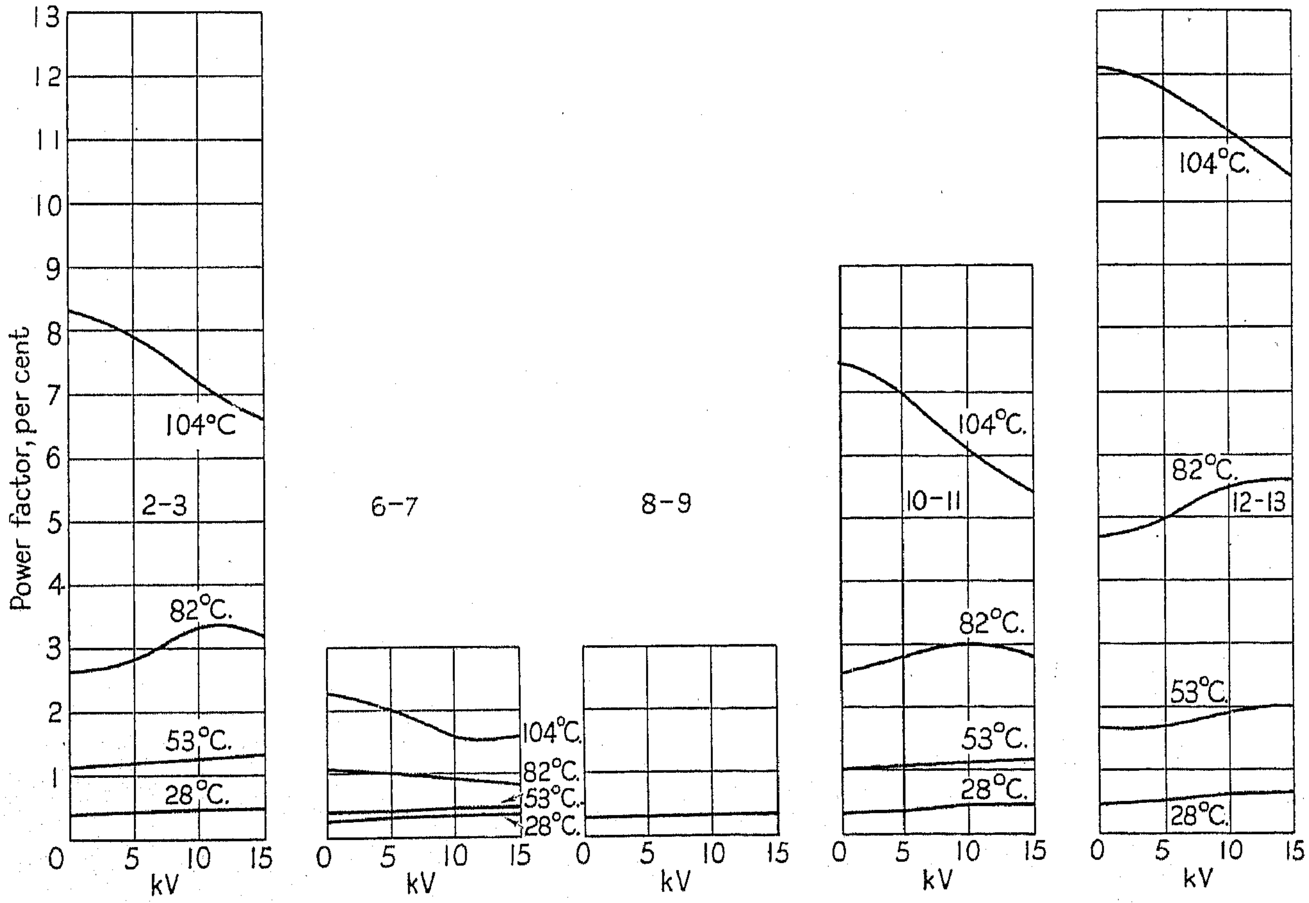

Fig. 5.—Analysis of power-factor/temperature characteristics of Cable No. EC.62/1 (red phase).

Radial power-factor tests have confirmed that the maximum of the loss curve is located in the outer papers of each core. Both rising and falling power-factor/voltage characteristics are obtained at the higher temperatures. Their occurrence is not completely explicable in every detail, but the falling loss characteristic probably arises from the modified radial voltage distribution which occurs with rise of testing voltage at the higher temperatures.

Both a.c. and d.c. puncture tests were carried out on the various sections of the aged cable, but the diminution of strength was of a very small order in comparison with the normal variations as between different tests.

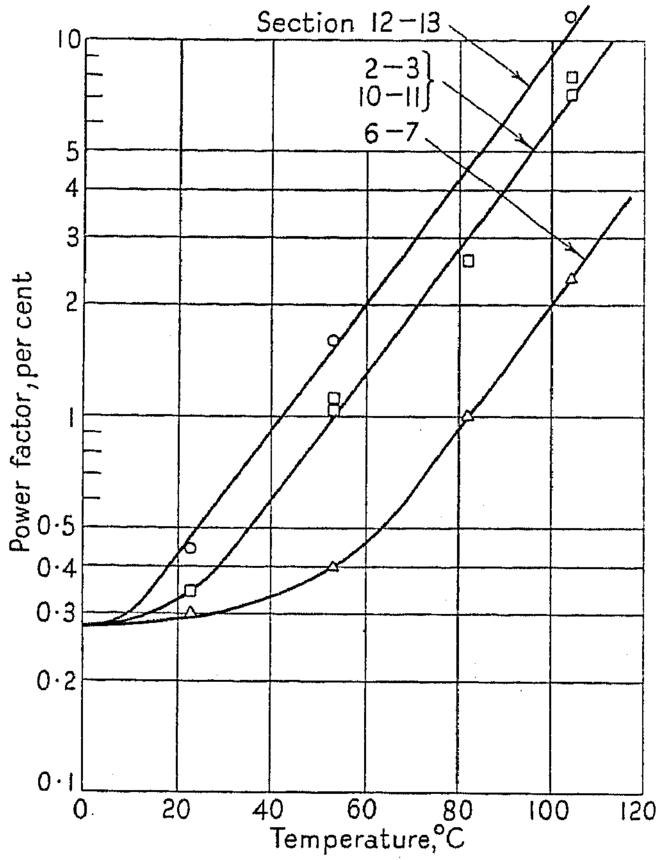

Fig. 6.—Relation between power factor and temperature, for Cable No. EC.62/1 (red phase).

(3.22) 60-kV 0·2-sq. in. single-core S.R. cable, 0·57-in. insulation (No. E.C.47/10a).

This cable was manufactured and impregnated after sheathing in 1933. Some 48 yards of the manufactured length were installed on racks and subjected to the ageing test illustrated in Fig. 8. The cable showed extremely good stability both on voltage alone and with severe heat cycles. After 83 days of testing, a cable elsewhere on the loop broke down, and the subsequent handling associated with its rejointing induced a moderate amount of ionization.

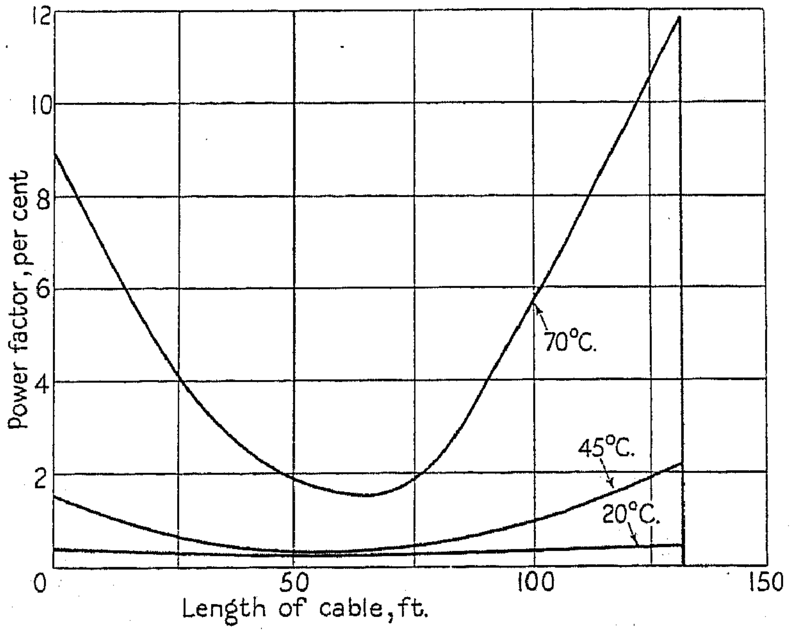

Fig. 7.—Distribution of power factor, for Cable No. EC.62/1.

After 101 days the cable was removed from test without breakdown. It was cut up into five sections, and the test results obtained are given in Tables 1 and 2. It will be seen that the ionization factor after cutting into sections has become negligible. The visual deterioration proved to be extremely small. The basic power-factor showed large variations along the cable length, and it is probable that the increase in dielectric loss at higher temperatures was pronounced in some parts of the cable. The short-time breakdown strength represents an appreciable diminution compared with that of new cable.

Table 1

ANALYSIS OF CABLE NO. EC.47/10a

Section		(1–2)	(3–4)	(5–6)	(7–8)	(9–10)
Test voltage (kV)		Power factor (per cent)				
15		0·586	0·498	0·492	0·420	0·484
25		0·586	0·498	0·493	0·420	0·484
35		0·586	0·498	0·493	0·420	0·485
45		0·587	0·499	0·494	0·420	0·485
60		0·589	0·499	0·495	0·421	0·485
75		0·589	0·500	0·496	0·424	0·485
Ionization (per cent)		0·001	0·001	0·002	0·000	0·001
Percentage change in capacitance, 15 to 45 kV ..		0·001	0·001	0·001	0·001	0·001
Short-time breakdown test	(kV)	180	180	160	180	180
	(min.)	56	49	62	62	31

Table 2

VISUAL DETERIORATION OF CABLE NO. EC.47/10a

Sample	1	2 : 3	4 : 5	6 : 7	8 : 9	10
Conductor						
First 60 papers ..	8·95	8·95	8·8	8·3	8·6	8·4
Second 60 papers	8·95	8·95	8·9	8·65	8·65	8·6

(3.23) 60-kV 0·2-sq. in. single-core cables, 0·65-in. insulation, 1934 (Nos. EC.58/1a and EC.59/1a).

These two cables were tested for the purpose of comparing the performance of different paper types. Sixty yards of each were involved in the present test, although reference is made elsewhere to check tests on shorter lengths. The former cable was graded with the least dense paper nearest the conductor, whilst the reverse held in the case of Cable No. EC.59/1.

The life-test histories of these cables are shown in Figs. 9 and 10. It will be seen that the cables, although not tested simultaneously, were subjected to conditions

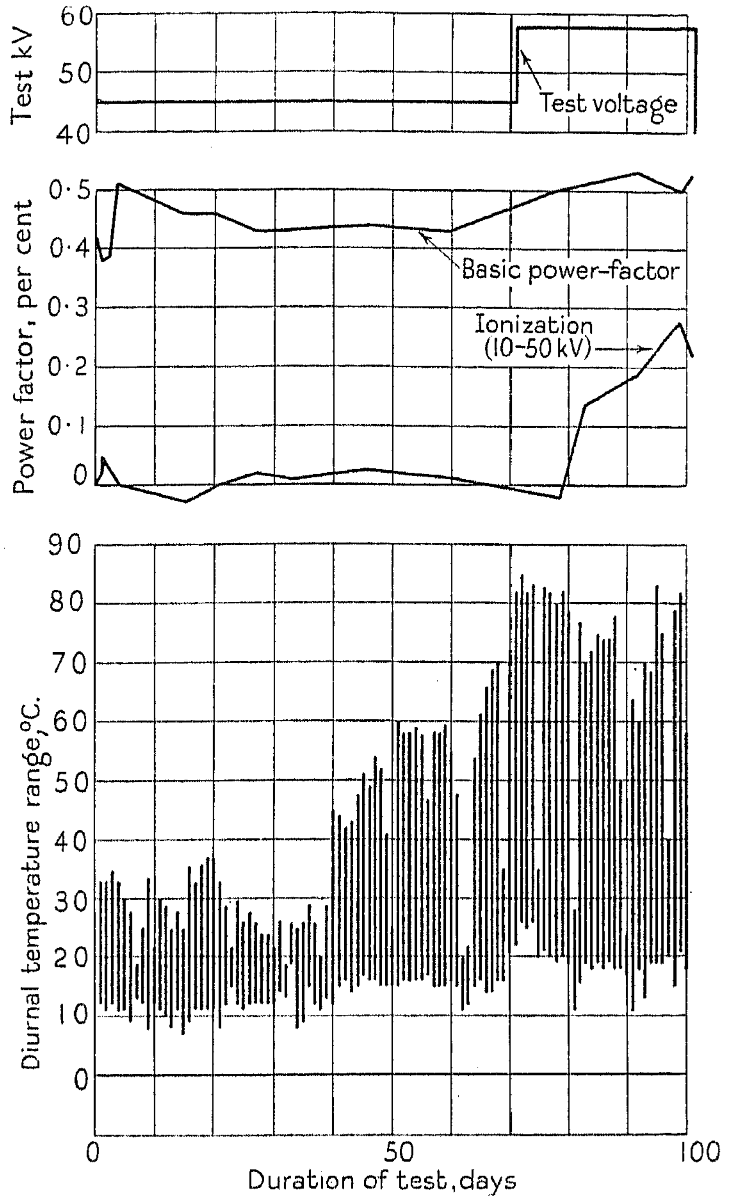

Fig. 8.—Life-test history of Cable No. EC.47/10a.

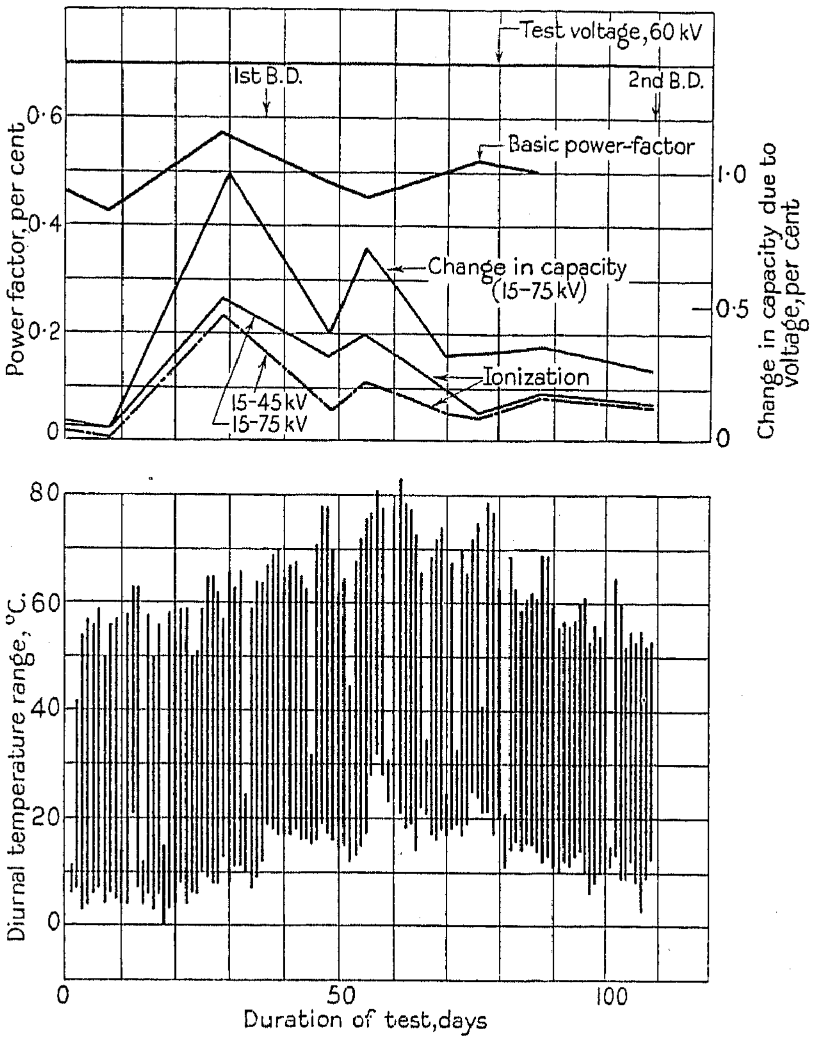

Fig. 10.—Life-test history of Cable No. EC.59/1a.

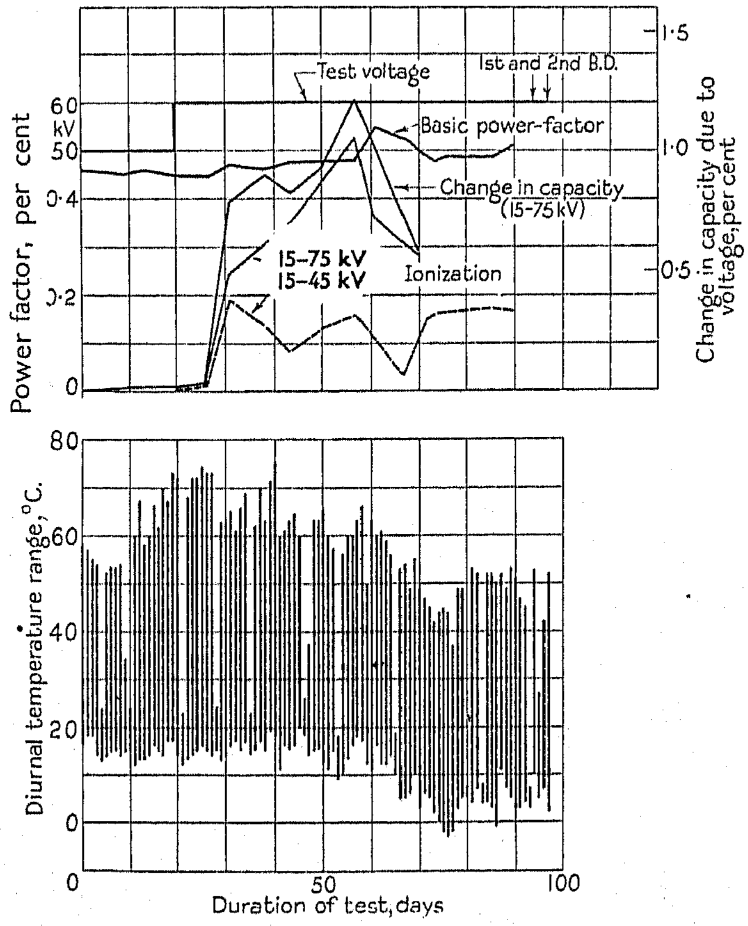

Fig. 9.—Life-test history of Cable No. EC.58/1a.

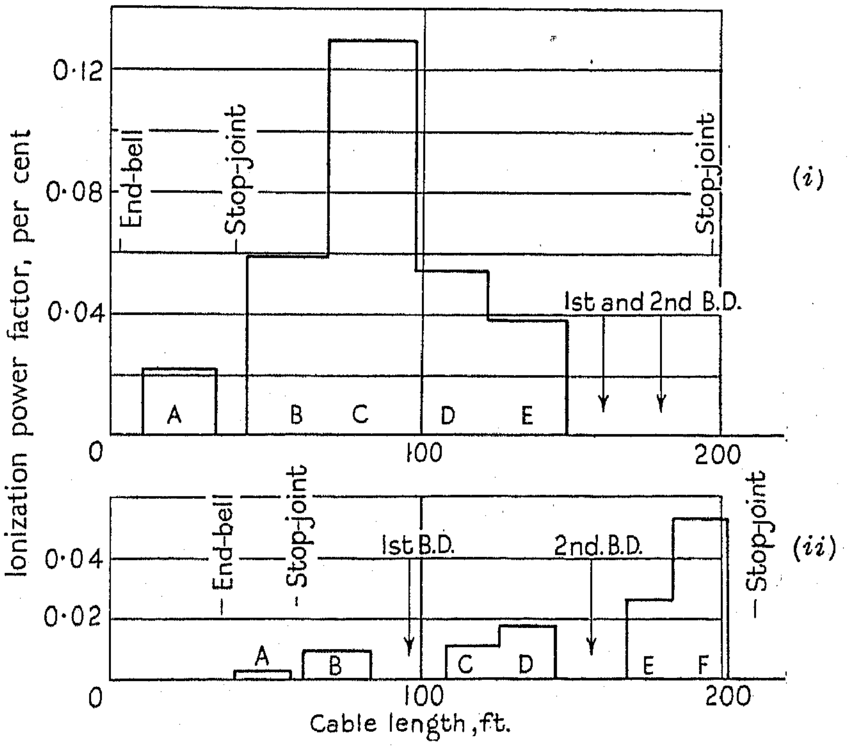

Fig. 11.—Distribution of ionization in aged cable.

(i) Cable No. EC.58/1a.
(ii) Cable No. EC.59/1a.

similar in severity. In the case of EC.58/1a, the two breakdowns followed closely upon one another and were associated with a thorough deterioration of the dielectric. In the other case the failures were widely separated in time and the cable remained at the conclusion of the test fairly sound in quality as judged by the authors' usual criteria. The analysis of these tests is best indicated graphically as shown in Figs. 11 and 12. The variation in ionization along the cable length is explicable in terms of the impregnation process, and it is reassuring to note that the service breakdowns are not coincident with the parts most severely deteriorated. Certainly, however, in the case of EC.58/1 the short-time breakdown strength does show some correlation with this deterioration, and this provides an indication of the usefulness of the test in indicating deterioration. The good performance of the sections immediately adjacent to the end bells is very marked (test point A, Fig. 12).

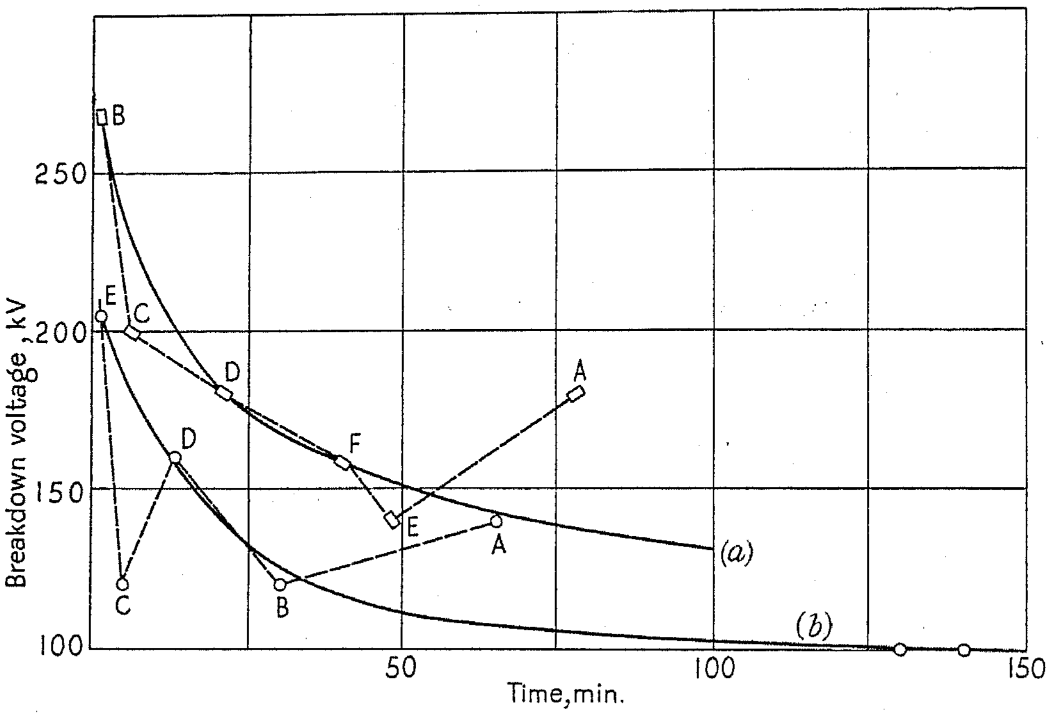

Fig. 12.—Electric strength of aged cable.

(*a*) Cable No. EC.59/1a.
(*b*) Cable No. EC.58/1a.

The discrepancy between the ionization of the installed lines (Figs. 9 and 10) and that of the aggregated sections (Fig. 11) is not so marked as in the previous case (EC.47/10a), and the difference may be a consequence of the different pressure conditions in the two cases.

(3.24) 60-kV 0·225-sq. in. M.C. (multi-conductor) cable, total radial insulation 0·445 in. (No. EC.63/2).

This cable represented the first attempt to construct a cable of the design illustrated in Fig. 2 and was one of a series which have given identical performance to date and which incorporate various experiments in paper types. It may be noted here that the intersheath design in question is not notably economical for this size of cable, but it was considered useful to adapt the design to this voltage rating in order to gain initial experience in direct comparison with normal types of which the performance is now well established. On a stress basis it will be seen that the performance (Fig. 13) is very satisfactory to date, so that one may assume that the practical difficulties in achieving the theoretical design are outweighed by such advantages as the reduced wall thickness and the physical construction.

It may be mentioned that the unusual trend in power-factor and ionization characteristics is not considered to be inherent and has been explained by Tschiassny* in terms of the intersheath construction. The failure of an oil joint after 112 days must be explained by the limited experimental work possible at the time of construction, in conjunction with the severe testing conditions. Its failure provided an opportunity for examination of a cable sample removed from the end near the joint. No visual deterioration could be detected. The cable was repaired with a joint having a higher factor of safety and has proved to be entirely satisfactory up to the present time.

The comparatively small temperature range of this test arises from the inherently low thermal resistance of this design of cable.

(3.25) 132-kV 0·3-sq. in. M.C. cable, total radial insulation 1·00 in. (No. EC.72/1).

The preliminary stability tests of this design of cable are included here in order to round off the range of voltage ratings of which examples have been quoted in this section.

A 150-yard length of cable is terminated in standard 60-kV end-bells, one of which is set up in a conventional manner with a reinforcing paper roll, the other being fitted with a condenser cone. The cable is arranged in a bifilar loop in troughs filled with sand; with the spacing adopted, the sheath circulating-current losses amount to nearly 45 % of the copper losses. Loading-current cycles of 350 amp. were used in the early part of the test, and at a later stage the loading was increased to 400 amp. The operating range of temperature is indicated in Fig. 14, which covers the life history of the cable for 200 days. At

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* See Reference (7).

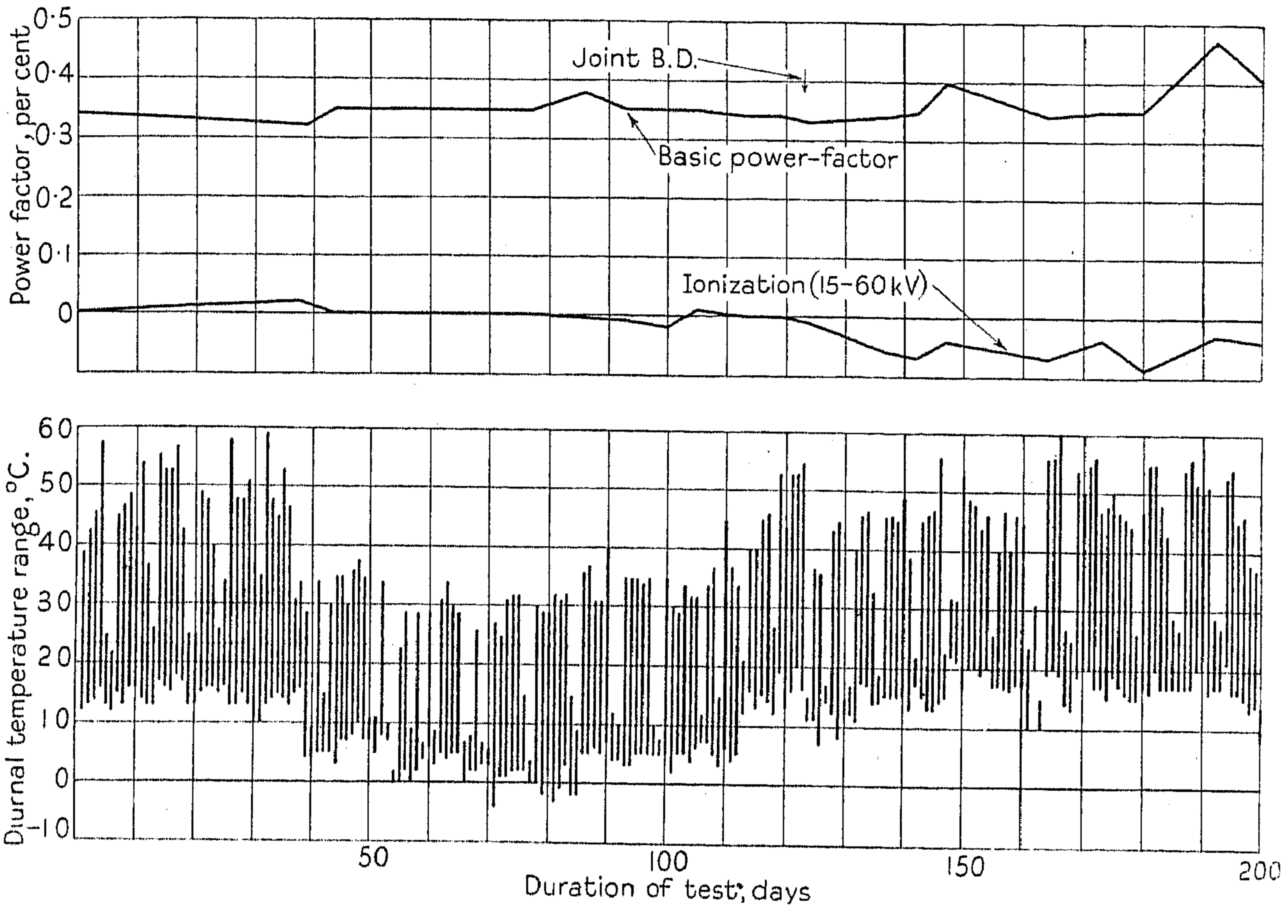

Fig. 13.—Life-test history of Cable No. EC.63/2. (Test voltage 60 kV.)

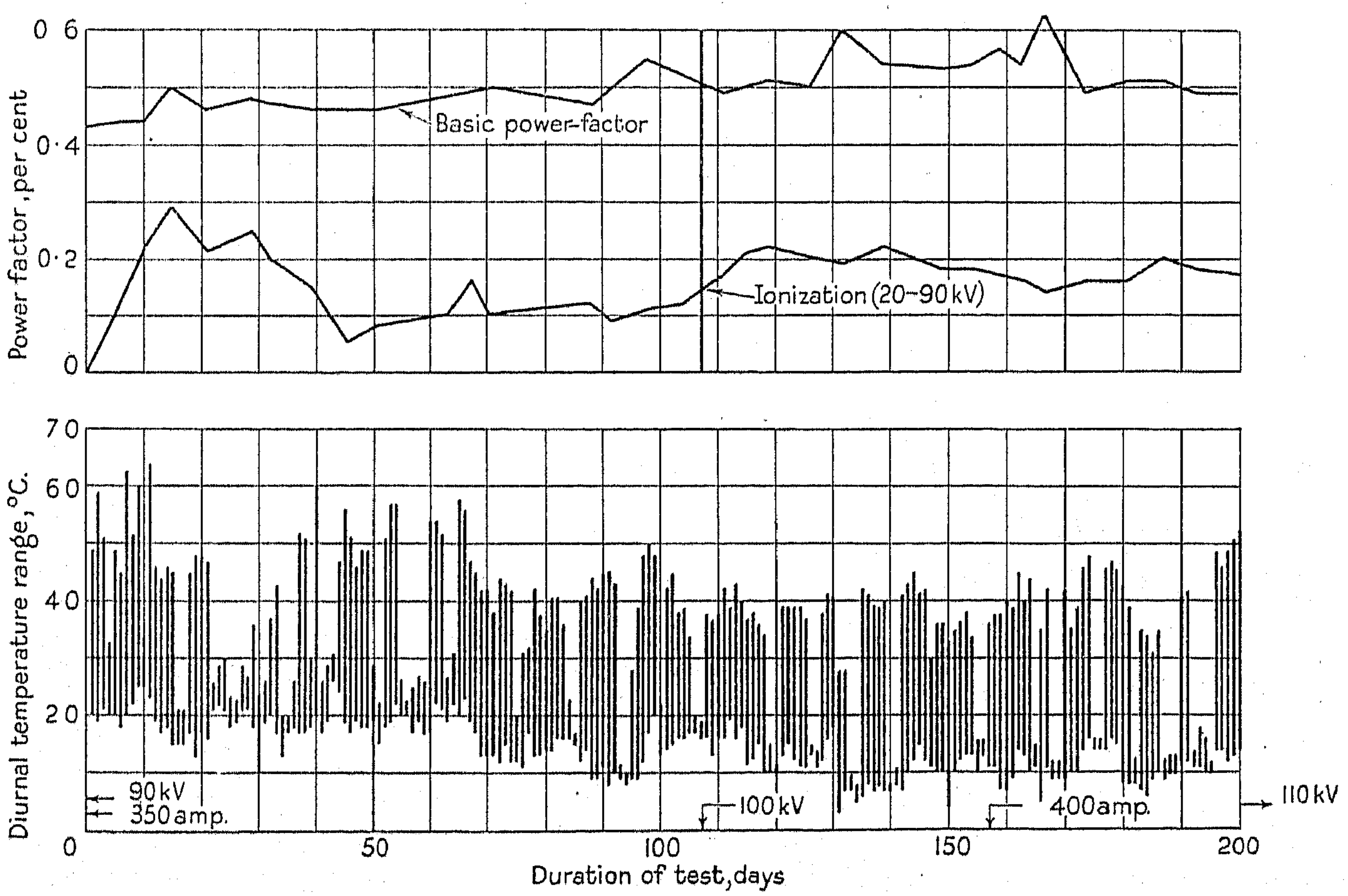

Fig. 14.—Life-test history of Cable No. EC.72/1.

the time of writing (October, 1938) the cable has just completed a 1-year period of test (365 days) and is proceeding under 115 kV, i.e. 50 % over-voltage. At 350 days the basic power-factor was 0·59 % and the ionization factor (20–90 kV) 0·11 %. The ionization factor from 20 to 120 kV was 0·14 %; owing to limitations in the test circuit it has not been found possible to exceed 120 kV.

(3.3) Ageing Characteristics

(3.31) The relation between voltage and life.

It is a fundamental necessity for the correct interpretation of any over-voltage test to establish the relationship between voltage and time-to-breakdown. In view of the expense and the time involved in carrying out accelerated ageing tests, it is not suprising that, so far as the authors are aware, no curves have yet been published showing this relationship in the neighbourhood of the operating stresses. Failing such information, many investigators have attempted to extrapolate results obtained from relatively short-time tests extending up to, say, 100 hours, and by the adoption of some inverse power law have attempted to assess accordingly the life of the cable at its rated voltage. An objection to this criterion of cable quality is based on the totally distinct mechanisms of breakdown in the two cases, and although short-time tests of this character may be informative and useful, any extrapolation to operating stresses may give rise to misleading deductions. In the short-time test, resistance to breakdown is provided by the " solid phase " of the cable; breakdown in service is effected by a deterioration mechanism which partially by-passes that obstructive barrier.

The large number of individual cables subjected to test within the period covered by the present report has tempted the authors to demonstrate the continuous improvement that has been effected within that period by plotting the maximum stress of testing against the time of test to the first breakdown on the cable-length in question (Fig. 15). In a few cases where the testing voltage was varied during the test an inverse power relation of 20 was employed to convert times to the higher-stress value. The improvements noted may be ascribed to reduced rate of deterioration and to greater uniformity of manufacture, along lines which will be described in succeeding sections of this paper. Maximum stress has been adopted as ordinate in the light of the observation that, with the present method of manufacture of cable, deterioration commences at the conductor. No doubt average stress and dielectric thickness will affect results to some extent, but in the authors' experience their influence is surprisingly small. The range of insulation thickness covered by these tests extends from 0·25 in. to 1·00 in.

In view of the observed irregularity of deterioration the practice has arisen in the case of test-lengths of the order of 50 yards of permitting two breakdowns to occur before finally removing the cable from test. In the course of the testing a large number of breakdowns have naturally taken place, but only one has occurred during power-factor tests, and since these tests almost invariably involve voltages higher than the normal test pressure, it is deduced that the final stage of breakdown takes place relatively suddenly; on the other hand, there is evidence to show that at the stresses with which we are concerned here, disruptive discharges may persist for periods longer than 1 day. The incidence of the greater number of breakdowns to the earlier hours of the morning, or more generally to some phase of the cooling cycle, is in line with practical experience in service.

In the case of cable manufactured in the early stages of the period under discussion, a breakdown was invariably found to have associated with it a considerable amount of burning in the central portion of the insulation. The breakdown path was of the tracking type described by Robinson, and was usually of very extended cross-section. With more recent cable the appearance is radically different. The central carbonized parts, due undoubtedly to poor impregnation, have quite disappeared. The tracking mechanism may still remain, but the path of breakdown is concentrated within a narrow compass although it may break up into two or even three channels towards the metallic conductors. Sometimes it is a straight radial breakdown, but usually in the present tests it extends over 2–3 ft. and is typical of a certain type of service breakdown.

Table 3

Cable	Test length (yd.)	Days of test	kV	Operating temperature range (°C.)	Remarks
EC.58/1a	60	19·4	50	− 1 to 70	
		+ 74·7	60		1st B.D.
		19·4	50		
		+ 75·5	60		2nd B.D.
EC.58/1b	30	133·6	60	− 2 to 79	1st B.D.
EC.58/2a	60	19·4	50	5 to 70	
		+ 48·6	60		1st B.D.
		19·4	50		
		+ 51·2	60		2nd B.D.
EC.58/2b	30	72·8	60	− 1 to 78	1st B.D.
EC.59/1a	60	36·7	60	1 to 86	1st B.D.
		109·2	60		2nd B.D.
EC.59/1b	30	107·3	60	− 2 to 79	No B.D.

The cable in the immediate neighbourhood of a fault is seldom damaged, and it has been the authors' practice to cut out only about 6 ft. on either side, when rejointing to bring a cable loop under test again. No ill effects resulting from this practice have been detected.

Into this section of the paper may be inserted some remarks relating to the effect of the length of cable under test upon the results obtained. Obviously a very extended research would be necessary to set this relationship upon a firm basis; it cannot be claimed that this research has been completed. Nevertheless, it is possible to quote the case of three cables, each of which was tested in two lengths of 30 and 60 yards. There was a difference in the conditions of testing in that the shorter lengths were jointed by means of oil-impregnated paper tapes, whereas the longer lengths were fitted with solid-type barrier joints in accordance with the authors' normal practice. The results are summarized in Table 3.

These tests were carried out under conditions which were in other respects as nearly comparable as possible. The trend of the effect is unmistakably in the direction of giving the longer test-length a shorter life on voltage. At the same time the evidence of more rapid deterioration is not confined to an observation of the time to breakdown, but extends to the other criteria referred to elsewhere in this paper.

It will be seen from the three curves of Fig. 15 that the asymptotic value of stress at which breakdown is delayed to times of the order of years has been increased to about 5·6 kV per mm. Since the maximum stress at operating voltage has hitherto been limited by common practice to about 4·5 kV per mm. for 60-kV cables, it is considered that an adequate margin of safety exists in such cable. The record of such cable in service, however, is entirely a function of the uniformity achieved in the manufacture; in so far as a reasonable test-length has been employed, and since no breakdown has occurred at times appreciably shorter than those illustrated by the curves, it seems reasonable to anticipate that substantial freedom from trouble will be experienced.

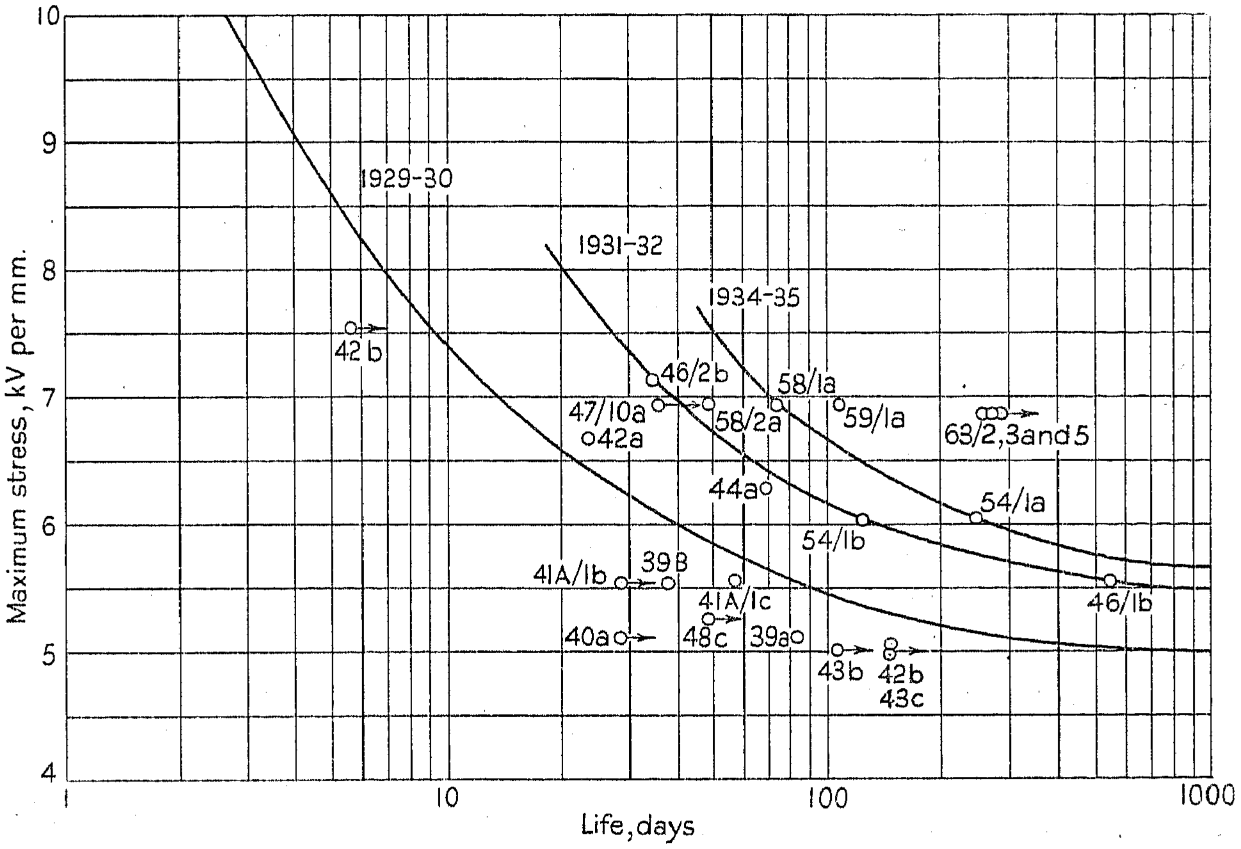

Fig. 15.—Trend of improvement in e.h.t. cable manufacture.

⟶ No breakdown.

Inasmuch as superior results are still being achieved with more recent cables, it is interesting to speculate upon the increase in operating stress which may become practicable with continued improvement in the quality of impregnated paper cable. In point of fact, cables have been recently manufactured and installed with maximum operating-stress values of the order of 5·0 kV per mm.

(3.32) Stability during ageing.

In any ageing test involving a reduction of the parameter time there is always a danger that effects which have the nature of a deterioration, but which are not susceptible to those other factors which are intensified, may be passed over unnoticed if considerable time is required for their development. A careful scrutiny of all physical phenomena occurring during life is therefore necessary to check back on conditions which obtain in service.

The effect of temperature upon the operation of solid-type cables has long been a source of speculation, and opinions still remain divided as to its importance as a factor in service performance. From a purely chemical point of view it has been established that little deterioration will arise from operation at maximum temperatures as high as 100° C. provided that suitable materials are employed. In the matter of physical stability it must be recognized that appreciable movement of a free conductor would take place in the range of temperatures involved, owing to the differential expansion of copper and lead: when the conductor has been suitably constrained, as in the normal case, no deleterious effects have been noted within temperature ranges of more than 80 deg. C. From the electrical point of view the information available remains far from conclusive: two effects are in question—an increase in loss due to a change in the compound akin to oxidation, and deterioration due to ionic bombardment.

As related elsewhere, it is the authors' custom to load their test cables so as to give a maximum copper temperature of not less than 75° C., which is as high as has yet been suggested for e.h.t. cable operation in this country.

Whilst it seems inevitable that the enhanced migration of compound which results from wider temperature ranges in operation must aggravate the progress of deterioration, this factor is not of serious importance with well-impregnated cable of low gas-content. It is difficult to quote direct experimental evidence to support this view.

Again, since it seems reasonable to assume that the major proportion of deterioration occurs at the periods during which the maximum void space exists in the electric field, the extent and the period of the minimum temperatures experienced would seem to be important. The authors' experience has tended to show a greater rate of deterioration during the winter months than in the summer, and this in spite of the less severe maximum temperature conditions that would be experienced in the former case. Equally it might be expected that cables maintained within a laboratory and lacking severe minimum-temperature conditions would show a better test record than those exposed to the inclemencies of the weather.

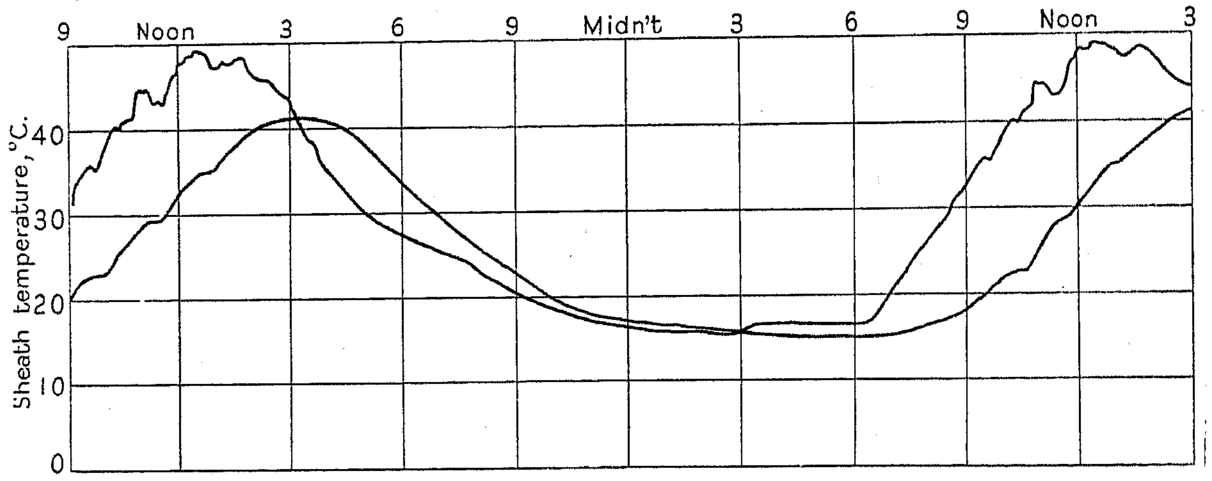

Fig. 16.—Sheath temperature of Cable No. EC.46A/1b, at 45 kV, without load, supported on racks. Results obtained 20th August, 1932.

Attention has been drawn to a longitudinal migration of compound which can be induced by differential heating of the cable.* In the earlier series of tests, in which the cables were supported on hangers attached to posts in the open air, similar temperature effects were induced by varied exposure to sun and wind, according to the location of the cable in relation to a brick wall which ran along two sides of the cable field. In view of the interest of the problem from the point of view of the practical case of railway feeders, where it is usual to support the cable in the open, typical records obtained from thermocouples placed on the cable sheath at two differing locations are shown in Fig. 16.

The authors' measurements of the pressures arising within the cable have not been as complete as have been those of some other workers in this field,† but they have sufficed to show that extremely low vacua can persist within the cable, and are not essentially incompatible with the most complete stability of the active dielectric. Extremely high pressures are observed during the initial heat cycles, and the nature of the expansion is such that in general the extension of the sheath cannot be effected elastically. The lead sheath "flows" under the strain, and creep also sets in, so that the excessive maximum pressures are relieved and a radial space of the order of 10–20 mils is set up between dielectric and sheath.

This effect may be related to the gradual lowering of cable capacitance (of the order of 3 %) which has been observed to reach its maximum after more than a week's testing, or about 8 severe loading cycles. It is felt that this is a demonstration of the gradual migration of compound to the exterior of the dielectric as the elastic return of the lead sheath falls away.

It is the authors' belief that the stability of the basic power-factor is very sensitive to the quantity and nature of the residual gas in the cable: the gases absorbed at the solid/gas interface of a dry-core cable will depend largely on the degree of vacuum existing immediately prior to impregnation. The practice of impregnating after sheathing has been largely adopted in the case of cables referred to here, and the excellent conditions which obtain contribute not a little to the stability revealed in these tests. A change in the basic power-factor has rarely been observed in the course of these tests, and it has been the practice to detect such changes as may have occurred by means of measurements carried out at the conclusion of the ageing test.

Experience in the matter of the ionization stability of cables under test has been varied: this matter is better understood now that the factors affecting the breakdown mechanism are appreciated. By extreme care in the evacuation and impregnation it is possible to produce cable with an extremely low ionization value, and such cable will maintain stability right up to breakdown in conditions involving severe loading cycles and test stresses of the order of 6·5 kV per mm.: in these circumstances deterioration will be found to be local, and the major proportion of the dielectric in quite sound condition. In yet other cases, power-factor instability will often set in relatively suddenly, and gradually build up a steady value followed by a slight recovery. These conditions will hold until a breakdown occurs. When a cable starts life with a fair measure of ionization, a slight cleaning-up may occur in the early stages, followed by a steady rise to some limiting value. A typical case is shown in Fig. 17, which illustrates the stability of Cable No. EC.54/1a during life: it is believed that this demonstrates an intrinsic feature of solid-type cable dielectrics.

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* See Reference (8).

† *Ibid.*, (9).

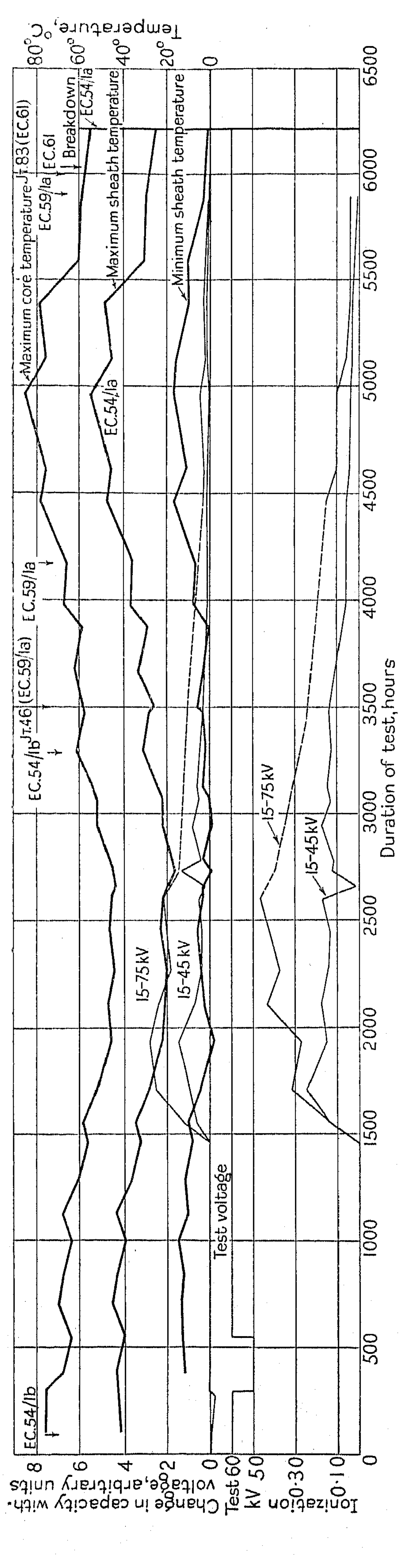

Fig. 17.—Life-test history of Cable No. EC.54/1a.

In the Figure the failure of other cables and joints in the loop under test are indicated. There is no evidence that these failures in any way influenced the life history of Cable No. EC.54/1a.

The problem in these observations is to determine the distribution of the ionization along the cable length. In the present circumstances it is impossible to interpret power-factor readings with any assurance of certainty. When an appreciable amount of ionization exists in a cable under continuous test, it will often be found that instability, marked by a steeply rising power factor/voltage characteristic, will set in at voltages above the continuous test voltage. If, however, the test voltage be raised the power factor of the cable will fall with time until an equilibrium condition is set up, so that the voltage at which instability begins is raised correspondingly.

In view of the great sensitivity possible in the measurement of capacitance, it was anticipated that the variation of capacitance with time and testing voltage in a manner parallel to that of ionization might provide useful information regarding the progress of deterioration in a cable. From a theoretical standpoint the change in capacitance of the whole dielectric is bound up with the state of ionization in the voids within that dielectric. At the moment these hopes have not been realized, for two reasons: (i) the variation of capacitance with temperature, and (ii) the inaccuracies involved in the authors' measurement of capacitance owing to variations in the value of the insulation resistance between earth and sheath. With refinements in the latter regard, it is felt that the earlier hopes may yet be realized.

(3.33) Tests after ageing.

General.—It has been suggested, on the strength of the information given in Fig. 15, that the general voltage/life characteristics of solid-type cables manufactured and installed in accordance with modern methods is sufficiently satisfactory to permit of cables up to 60 kV being operated at the stresses normally employed. This conclusion must be dependent upon an estimate of the uniformity of the cable, both from length to length and along each individual length. For this reason every cable removed from an ageing test is examined carefully in order to assess the deterioration which it has undergone and to observe its distribution relative to the manufactured or installed length. Furthermore, the whole technique of cable development as revealed in this paper rests upon our ability to locate the source of every form of deterioration and to discover the reason for any observed non-uniformity.

The tests which are normally employed in these cases have been listed in Section (2.32), and it only remains to record here the general nature of the effects observed, together with some examples of interesting results obtained. With the refinement of the testing methods, it becomes possible to carry out measurements on comparatively small samples of cable, whereas in the earlier stages of development it was not possible to carry out the complete programme of tests as detailed below.

At the conclusion of an ageing test the remaining length of sound cable is cut into a convenient number of lengths suitable for breakdown tests: further short samples are removed from the ends of each of these short lengths for the purposes of visual-examination tests, radial (tape) tests, and power factor/temperature tests. The lengths selected for breakdown tests are prepared so as to permit power factor/voltage observations to be taken prior to breakdown.

Visual examination.—It is now many years since the formation of waxy products from the impregnating compound was first discovered in high-voltage cable, and it has long been recognized that while the " cheese " itself is a dielectric of some merit, its occurrence is an indication of deterioration in so far as the gas which is produced simultaneously militates against the indefinite operation of the cable. More recently it has been suggested that the mere production of wax in a cable is not an indication of deterioration, and since opinion may perhaps swing too far from the truth in this direction it would seem worth while to discuss the authors' experience in regard to its occurrence.

Among the cases in which breakdown has taken place during accelerated ageing tests, examination has shown examples in which cheese has been present and also others in which it has been absent. In the latter cases it is invariably found that the breakdown is not associated with the complete deterioration of the insulation, and if the remainder of the cable is again submitted to test it may be anticipated that succeeding failures will not take place for some little time; in these cases also it is sometimes possible, if the failure is interrupted in the incipient stage, to detect some discontinuity in the dielectric which is responsible for the discharge causing the failure. The remaining cases are found to cover a wide range of cheese-formation, ranging from a slight thickening of the compound to a complete metamorphosis of the compound, so that for more than 80 % of the radial thickness the paper has the appearance of having been completely impregnated with wax: in spite of the absolute absence of dendritic markings or of any carbon whatsoever, the breakdown strength of the cable will be found in an extreme case to be reduced to less than 50 % of its original value. On the other hand, the production of cheese during the life of a cable is long drawn out, so that its presence is by no means an indication of impending cable breakdown.

Wax formation is the result of electrical discharges playing upon the film of compound, so that it first occurs in the neighbourhood of the gaps. It would seem possible, from the authors' experience, to slow up the process indefinitely at stresses up to 7 kV per mm. by reducing the gas content of the cable. On the other hand, it has been observed that within the cable there are invariably taking place discharges which can be heard either by the unaided ear placed in close proximity to the sheath or by a sensitive radio-receiver coupled to a suitably placed antenna; these discharges may persist down to very low stresses. The former method permits a very accurate location of their source and even allows the severity of the discharge to be assessed in qualitative terms. The distribution along the cable length has been found to follow very closely the known variation in the quality of impregnation.

In the search for a relationship between ageing tests and service performance, the appearance of the dielectric from the point of view of cheese formation is a most useful criterion. Fig. 18 represents the mean of some half-dozen tests carried out in the manner described in Section (2.32) and Appendix 1 on a length of aged cable, the samples being removed at equidistant intervals from a length of Cable No. EC.54/1a. The radial distribution gives a very fine measure of the uniformity of impregnation. In the light of the conclusions reached as a result of the present tests, it is not surprising that in all the examinations of cable removed from service the occurrence of wax has been found to be entirely spasmodic and restricted to comparatively small sections of a length.

From this point of view, most surprising has been the experience obtained from some 60-kV 3-core cable manufactured in 1928, which was removed and tested after about 2 years' service and was found to be entirely free from cheese formation; on a subsequent ageing test it has remained irreproachable in comparison with other cable. Corresponding single-core cable manufactured at the same time, although built with 0·55-in. wall thickness as against 0·52 in. in the case of the 3-core cable, formed considerable wax in the course of an equal period of service.

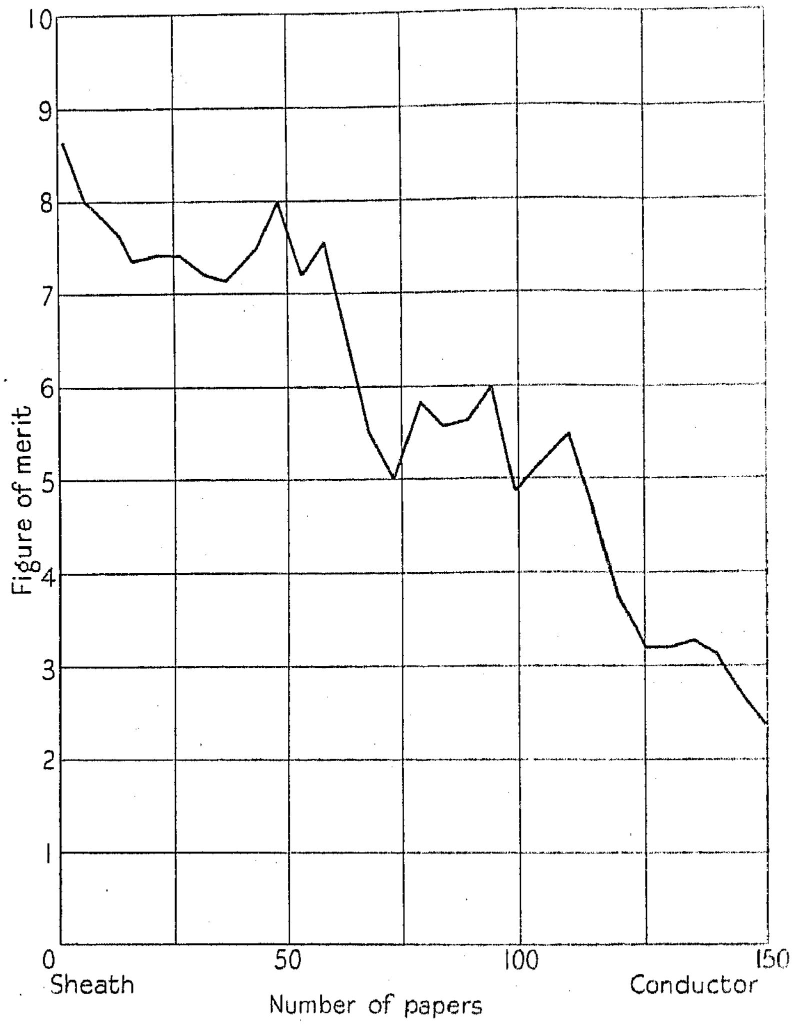

Fig. 18.—Radial distribution of deterioration in Cable No. EC.54/1a (visual examination).

60-kV cable of 1931 manufacture has been examined after about 3 years' service, and again a limited amount of wax formation has been detected, but by the short-time breakdown tests which the authors have devised to evaluate the importance of the deterioration they have been able to confirm their preliminary estimate that the ageing of this cable was not excessive.

In the 30-kV field one may judge from the value of maximum stress for which these cables are designed that the occurrence of cheese should be delayed for many years of service, and this has been borne out by the authors' general experience. In a number of cases where slight waxing has been found, its incidence has been shown to be associated with manufacturing defects such as have been pointed out in the course of this paper. In particular, the increase of gas content in the vicinity of joints has been responsible for wax formation in cases in which the internal pressure of the cable has reached low values.

Basic power-factor.—The basic power-factor at atmospheric temperature is largely, though not entirely, determined by the paper component: at higher temperatures the loss becomes increasingly a function of the impregnant.

The power factor of new cable impregnated with virgin compound often decreases with rise in temperature, but with the passage of time and the incidence of heating the position will change to the extent that the oil becomes oxidized. It has been observed that, although oils will not alter appreciably when maintained at 120° C. under vacuum, the presence of lead or copper will permit an increase of dielectric loss to take place even though negligible gaseous oxygen is present. From this arises the authors' observation that the very nature of the impregnation, as well as the history of its subsequent service, will affect the stability of the basic power-factor of the cable.

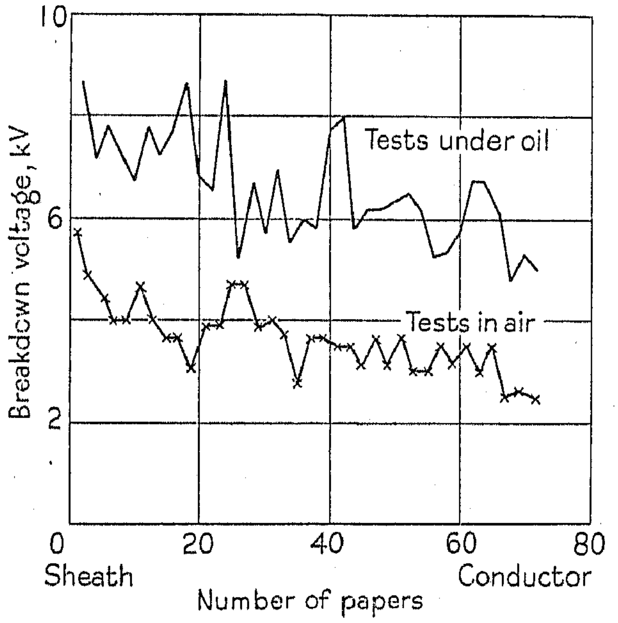

Fig. 19.—Radial tests of a.c. breakdown on Cable No. 771/6d. Rate of increase of voltage, 50 kV per min.

In the normal tank process the flow of compound during impregnation is radial, but the oil which is oxidized in the presence of copper and lead during manufacture remains largely confined to the boundary layers of paper tape: in service, however, this oil tends to become more dispersed. In the sheath-impregnation process the longitudinal flow of compound and its maintenance at an elevated temperature for an appreciable time involves the compound in an oxidation which may affect the basic power-factor of a cable.

In service, the losses associated with the paper will seldom vary, but the effect of conduction in the saturant will, with increasing oxidation, be translated to continually lower temperatures. The rate of oxidation will be determined by a number of factors such as the type of compound, the range of temperature, and the presence of oxygen and such catalysts as copper and lead. As a result the critical temperature for thermal instability is lowered with ageing, and this may impose a limiting factor upon the operating temperature of high-voltage cable. Some examples of the power factor/temperature relations of aged cable have already been given, and the need for precautions in manufacture and installation has already been emphasized.

Ionization factor.—Power-factor tests carried out on the lengths selected for the breakdown tests provide data for the distribution of the ionization factor along the cable length. It is very rare that the ionization factor obtained in this way checks with the ionization existing in the cable when it is on ageing test. Usually it will be lowered by opening up to the atmosphere, although it may be enhanced by severe mechanical disturbance of the cable. With the extremely stable cables produced to-day it is possible to relate the observed ionization to the conditions of impregnation (Fig. 11).

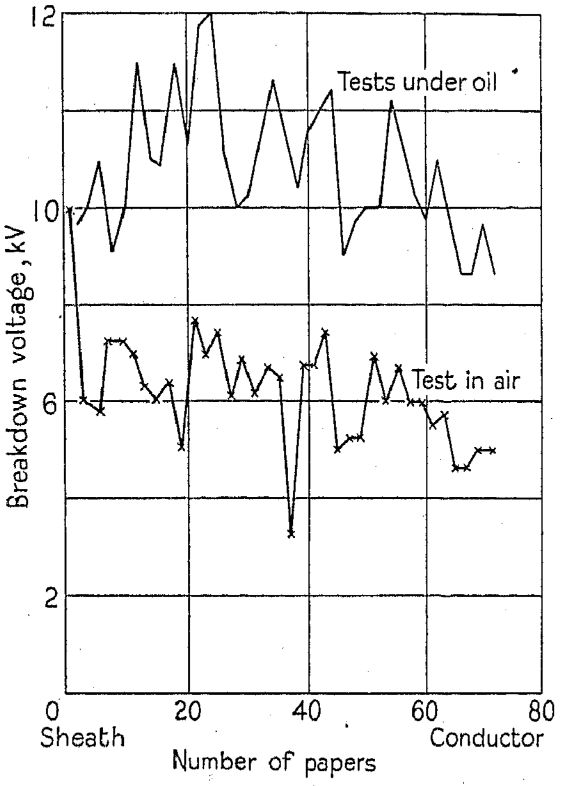

Fig. 20.—Radial tests of d.c. breakdown on Cable No. 771/6d.

Electric strength.—One further criterion which is believed to be important is the breakdown strength of aged cable under alternating stress and short testing-times. In such tests breakdown is invariably radial and the reduced strength arises no doubt from the manner in which the large amount of gas present assists the ionic bombardment of the paper fibres. Thermal instability probably intervenes at an early stage where the life of the cable has seen an increase in power factor due to the deterioration of the compound.

The authors' experience in the application of direct voltages to effect cable breakdown is limited, owing to the high inherent strength of the cables with which they are concerned. The effect of ageing is to reduce the strength, as in the case of alternating voltage.

Radial tests have been carried out on the breakdown voltage of tapes removed from deteriorated cable. The general trend of the results is in line with the degree of waxing, and sometimes a reduction in strength may be observed at the outer parts of the dielectric, corresponding with the observed increase in power factor. With such tests the effect of weak spots in the tapes is to create a wide scattering of individual results, which tends to be less when the tape is tested in air than when it is broken down under oil: the latter condition, however, would seem to approximate better to the case of a cable test, although in this case the integrated a.c. tape-tests invariably exceed the breakdown strength of the cable. Typical results obtained on aged cable are given in Figs. 19 and 20.

The correlation between such tests made with alternating current and with direct current is apparently subject to variations which are not completely understood; in practice the latter form of testing is more convenient, by reason of its lessened dependence upon the time factor.

(3.4) Discussion of Results

In view of the general silence on the subject, it has required some courage to assert the authors' conviction that quite a large proportion of the breakdowns experienced are due to mechanical defects in the cable insulation. This statement must be qualified by the observation that only in a very limited number of cases has it been possible to detect any visual signs of defects, even where the damage done by the breakdown was slight. At the same time, it is believed that the standards of mechanical uniformity attained in the cables described herein are not inferior to those prevailing in general practice.

The literature on the subject of impregnated-cable research has been largely concerned with improvements in the quality of the impregnation and with efforts to discover saturants with improved characteristics. The authors' own earlier work was also directed to this end. The development of the method of impregnating after sheathing not only effected a more uniform impregnation and a more complete elimination of gas but also provided an opportunity of studying the behaviour of different compounds under practical conditions of operation.

In proportion as the homogeneity of the cable produced has been improved in the course of the year which the present report covers, it has been possible to appreciate the extreme sensitivity of the cable performance to small inconsistencies in its make-up. For obvious reasons these mechanical defects assume the greatest importance in the immediate neighbourhood of a metallic conductor and also in the regions of highest electrical stress. Instances of these types of mechanical defect may be quoted:—

(i) In the case of overlapped tapes, whether of insulating papers or of interlocked metallized pairs, it is difficult to avoid periodic creases owing to the physical impossibility of securing a tight lapping in these circumstances. Overlapped tapes may be called for in the cable design, or they may arise from the faulty adjustment of the paper-lapping machine.

(ii) The centre of breakdown has been found to coincide with barely perceptible kinks in the strands of a conductor, and one is driven to the conclusion that these disturbances have been transmitted to a few of the succeeding papers, although visual evidence of this has not always been forthcoming. Brazed or welded joints in the individual strands occur periodically in the cable length, whilst only a sound factory routine can hope to eliminate the very slight accidental damage which can cause the present effect.

(iii) A creased tape is always a potential source of local discharge in proportion as the radial dimension of the gap space is increased: such creases may be caused by slackness in the mechanism of the lapping machine or by a badly-wound paper pad. This case may be distinguished from the case where a tape is creased along an adjacent gap owing to excessive bending or poor manufacture: in such a case the local breakdown strength may be lowered by the reduction in the " barrier action " of the paper due to its mechanical breakdown.

(iv) In the same category may be placed the local stress concentrations due to irregularities in the conductor contour caused by the stranding. A smooth contour is sometimes obtained by the use of shaped strand or by means of heavy crushing in the stranding operation, but in solid-type cable this may be subject to other disadvantages, such as the elimination of oil-reservoir volume and the creation of a less flexible core. A metallized-paper screening tape has been largely used in the present tests to achieve the same effect; it has the further advantage that, should the inner insulation be separated from the conductor, as by imperfect manufacture or by expansion of the conductor in service, the screen remains in intimate contact with the paper dielectric and the liability of discharge is thereby lessened.

In so far as the deterioration process has its source in the effect of electrical discharges on the impregnating compound, the lapping must be considered from the point of view of securing the best conditions for the limitation of these discharges consistent with the other requirements of the completed cable. It is proposed to treat in detail with this and other related aspects of the problem in another paper, and it is perhaps sufficient to summarize the authors' conclusions in the thesis that the space available to discharge, i.e. unoccupied by solid material, must have minimum dimensions, particularly in a radial sense, and must be uniformly distributed. Experience has shown that it is precisely this variation in the distribution of gap spaces within the insulation which often determines the location of the ultimate failure of the cable.

These considerations have led to a search for a quality test for the lapping process. Although no single comprehensive test is ever likely to embrace all the factors involved, some progress has been made in devising a series of related tests, and mention may be made here of the means the authors employ to evaluate the accuracy achieved in lapping. By the methods explained more fully in Appendix 1, there is obtained a distribution curve showing the percentage of tapes falling within a given range of break-joint: typical distribution curves are given in Fig. 21.* The curve is centred about the designed break-joint and demonstrates a mean divergence which is a measure of the accuracy achieved. A useful tool in estimating the uniformity of compactness is the Styrene wafer of Wyatt, Smart, and Reynar.*

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* The code employed to designate the cable makers is one that is peculiar to the authors' company.

In order to minimize the tracking type of failure it is necessary to ensure that the leakage paths connecting successive gaps are a maximum, a condition which requires a break-joint approaching 50 %. A designed break-joint of exactly 50 % may be objectionable from other points of view, so that the closeness to which the designed break-joint may approach 50 % must be determined by the accuracy with which the machine can be set up and the cable lapped.

In conclusion, some remarks may be made as to the effects due to the different cable types that have been tested.

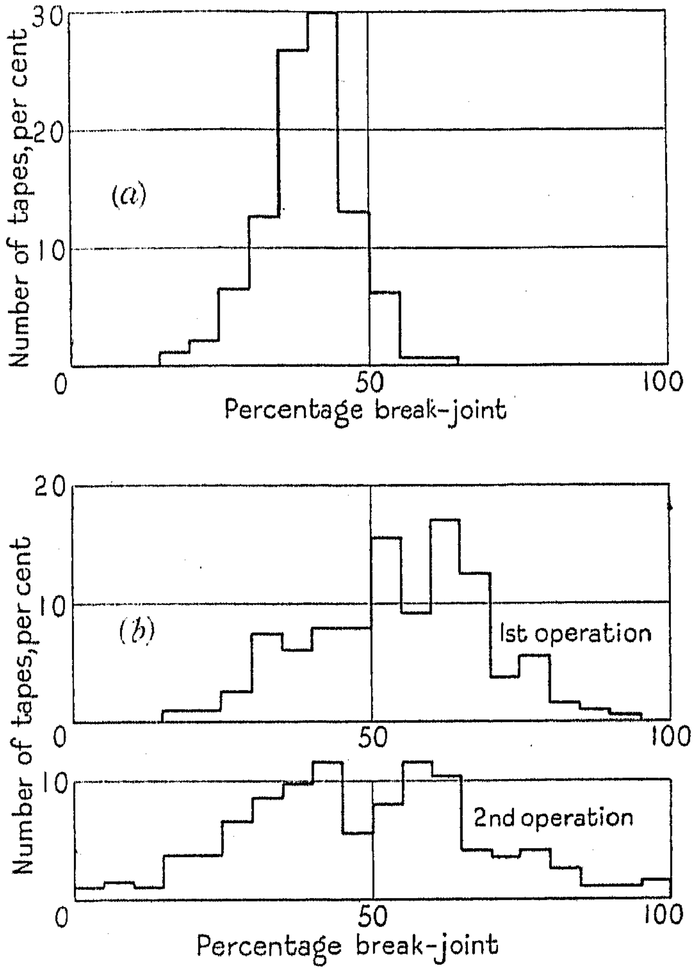

Fig. 21.—Lapping analysis of cable: good and bad registration.

(*a*) Cable-maker F (1935).
(*b*) Cable-maker B (1932).

(*a*) *Multi-core cables.*—Reference has already been made to the superior performance of multi-core as compared with single-core cable of comparable design. This observation is a general one, but one specific case has been quoted which illustrates the point most markedly. The vacua set up in this type of cable upon cooling are as high as those in single-core cable, thereby controverting one reason hitherto offered for the superior performance of multi-conductor cables.

(*b*) *Intersheath cables.*—There have been tested a number of cables which embodied an intersheath maintained at a floating potential and located at various parts of the dielectric. Whilst it cannot be claimed that this feature contributed anything to the satisfactory behaviour of these cables, their performance was observed to be in no way at variance with the general voltage/life curves shown in Fig. 15 and pertaining to their particular vintage. This is in line with the conclusions drawn elsewhere as to the nature of cable deterioration.

An objection has been raised that the intersheath permits the lining-up of separate points of weakness in the insulation so that ultimate failure may cause breakdowns to occur in more than one part of the cable. In the authors' experience this has not proved a serious matter, since breakdown of the inner belt alters the potential of the intersheath: the outer belt is well able to withstand the over-voltage for the period of time necessary to detect and protect against the initial fault.

(*c*) *Multi-conductor* (*intersheath*) *cables.*—This type of cable embodies features which belong to the previous types, so that the preceding observations apply equally in this case.

The outstanding advantages of reduction in the value of maximum stress do not extend to the case of the 60-kV cable of which the life-test history is quoted, but operate in the sphere of cables for rather higher voltages. However, the performance of the cable on a maximum-stress basis and, still more, on the basis of average stress, is extremely good in comparison with that of normal cables of similar quality. This must be attributed in the first place to the factors which also secure the good performance of normal cables of multi-core construction, but the fact that the "maximum insulation thickness" is reduced considerably in this design as compared with a standard cable is probably of importance.

(4) CONCLUSIONS

As a result of the experience gained in these tests, it is felt that the successful operation of solid-type cable at 60 kV is firmly established. The employment of this form of cable in preference to the other types which have been proposed should rest on a purely economic basis in which the cost of the installed line and its maintenance is added to the charges to be attributed to the electrical losses involved in operation. In this latter respect the stability of the dielectric of sound solid-core cable need be in no way inferior to that of other types.

The deterioration due to the electrical discharges in gas pockets can be reduced to negligible proportions at the proposed working stresses by due attention to the quality of manufacture. In this matter the authors' experience suggests that uniformity of impregnation is essential, rather than extreme quality.

The authors' knowledge of the possible increase in "basic" losses is seen to lack experience in the factor of extended time. The requisite elimination of moisture is readily obtained in manufacture and maintained in service, but the continued deterioration of compound is difficult to avoid absolutely. Nevertheless the authors' tests, conducted in circumstances far more unfavourable than can be guaranteed in practice, suggest that such deterioration is unlikely to be a vital factor in the operation of well-constructed and soundly installed cable. Provided that suitable precautions are taken, this effect can be reduced to very small proportions, so that these losses need not represent a limiting factor for the temperature range and the electrical stresses considered in this paper. In any event, the corresponding conditions are far more severe in the case of other cable types where the level of electrical stress is higher.

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* See Reference (10).

The solid-type cable will always be sensitive to relatively small variations in the physical make-up of the solid components, although the possibility of trouble arising from this cause can be very remote if the quality of impregnation be high. Consequently it is concluded that the property of mechanical uniformity is vital to successful operation. Obviously, the higher the stress at which the cable is worked, the greater the possibility of trouble arising from lack of uniformity. The problem of ensuring the reliability of 132-kV solid-type cables in service is one of quality testing to eliminate lengths of cable below a certain standard of mechanical uniformity, since economic considerations involve working such cables at relatively high stresses.

To establish the economic basis for the selection of the cable type to be adopted for any given application, it is the authors' strong feeling that the same temperature-limits may be employed for the class of cable treated here as are considered practicable for any type of impregnated paper cable. This applies both to absolute temperature and to the maximum range of operating temperature.

The present tests, covering, as they do, cable in which the "geometric factor" varies between wide limits, permit the observation that, with well-made cable, it is the maximum electrical stress which is the crucial factor in its behaviour in operation. While recognizing, of course, that the value of average stress will affect the rate of deterioration, the authors rather suggest that the maximum stresses considered in relation to the level of cable quality will decide whether or not that deterioration will commence.

The following two conclusions arising from these tests and relating to the installation of solid-core cable are put forward in the belief that they will commend themselves to the operating engineer:—

(i) It is impracticable to provide within an end-bell sufficient reservoir capacity to accommodate the dilatation of compound associated with a well-loaded cable. An auxiliary reservoir under a slight positive pressure may therefore be provided: this will serve to relieve excessive pressures, which are liable to cause oil leaks and to prevent vacua at the cable ends. Alternatively, a solid block may be inserted in the cable or in the cable-end to isolate the porcelain assembly from the main body of the cable: a number of methods of effecting this are available.

(ii) The most stable type of solid-core cable generates internal vacua over extended periods of service; this imposes stringent requirements in the matter of jointing. A pressure-fed joint is a possible solution, but is at variance with the authors' conception of a solid-type cable system. A satisfactory alternative is a solidly insulated joint which reproduces the cable dielectric and is able to withstand in service the incidence of low internal pressure.

The technique of long-period ageing tests as developed in this paper imposes more severe conditions than do other tests which have been reported. In particular, the use of medium lengths of cable with "solid" barrier joints creates conditions which are more nearly similar to those of cable as installed in service.

The greatest existing need in the sphere of solid-type cable is the formulation of an acceptance test which will be truly revealing and will serve to reject cable lengths containing potential faults: the best interests of cable-user and cable-maker alike would be served by such a test. Its adoption would permit an immediate substantial increase in the level of working stress in comparison with that proposed to-day. The possibilities of finding such a test cannot be estimated, and in default the wise cable-maker is forced to adopt an exacting form of process inspection which will prevent the occurrence of inhomogeneities which experience has shown to be the source of trouble in service. The measure of his success will only be revealed in the service records of his cable in the years which follow.

ACKNOWLEDGMENTS

In conclusion, the authors wish to acknowledge their indebtedness to Standard Telephones and Cables Limited for permission to publish the test data included in this paper, and also to Mr. J. K. Webb and other members of the laboratory staff of that Company for their co-operation. It is obvious that it is impossible to acknowledge individually each contribution in a paper covering a comprehensive series of tests extending over a long period of time.

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APPENDIX 1

Lapping Analysis

When successive tapes of equal width are applied to a cable with constant lay, the gap which separates their abutting edges tends to increase at a rate which depends upon the relative dimensions of the cable and the lay. In general practice it is usual to alter the lay from time to time: as a consequence the inter-tape gaps of successive tapes applied with different lays will be superimposed periodically along the cable length.

In considering tapes applied with the same lay it is important that succeeding gaps should be well separated: this separation is determined by the initial adjustment of the machine in conjunction with the " wander " of the tape on either side of its designed helical path. It is impracticable to study directly the position of each tape in relation to the cable length, but if its position relative to the preceding tape be observed for a large number of positions along the cable length it is possible to determine the two factors of mean break-joint and percentage " wander "; this is of value in relation to the development of a lapping machine. In its application to cable inspection it is sufficient to note the percentage break-joint of each tape at any one location relative to the preceding tape, where this tape is applied in the same direction with the same lay. A distribution curve may then be drawn up, as in Fig. 21, which gives a very clear picture of the order of adjustment that may be encountered.

A similar procedure may be followed in plotting the actual inter-tape gap, for this will indicate the actual " wander " of the tape, but it is necessary to interpret this curve in terms of the lapping design.

APPENDIX 2

Visual Assessment of Deterioration

The deterioration of a cable by waxing proceeds by well-recognized stages occurring throughout its useful life. Subject to a number of limitations, such as lack of uniformity, it is possible to assess its local severity. The appearance of the tape alters with time and exposure, and furthermore varies in its implications for different types of compound. Correlation between cables examined at different times and by different observers will therefore be difficult, but the method has been found extremely useful in noting longitudinal and radial variations in cable quality. Ten numbers have been allotted for these different stages:—

Scale of quality

10	perfect appearance.
9	oily appearance.
8	slight dry spots (near gaps).
7	dry spots.
6	oil thickening.
5	occasional wax (near gaps).
4	general wax.
3	prolific wax.
2	very prolific wax.
1	unwholesome waxed appearance.

A radial distribution of deterioration determined in this way from an average of seven sections is shown in Fig. 18.

DISCUSSION BEFORE THE TRANSMISSION SECTION, 18TH JANUARY, 1939

Mr. J. R. Beard: A large part of the paper is devoted to examining the practicability of cables with solid insulation for 66 and 132 kV. While I agree that cables which can be laid in the ground and forgotten are to be preferred to cables which require routine inspection and maintenance, it is only on the assumption that the former cables can be relied upon to give reliable service over extended periods. One or two faults on such a cable system may lead to very considerable indirect expense, and outweigh any capital or maintenance saving. Those who have experienced trouble with solid cables at these voltages in the past will, I think, need more assurance than this paper at present gives before risking the loss of that comparative peace of mind which they have experienced for many years with oil-filled cables and latterly to a limited extent with gas-pressure cables. In fact, it seems possible that a good deal of time and money may be lost in striving for a cable with solid insulation to be used at these voltages.

In their summary on page 69 of the fundamental points on which the economics of cable design depend the authors make no comparisons between the various types of cable mentioned. They point out that the working stress determines the insulation and to a considerable extent the cost of the cable, and on page 81 suggest that 5 kV per mm. gives an adequate margin for 60-kV solid cables; but from the curves in Fig. 15 the margin would seem to be negligible, whereas the French 220-kV oil cable operates at 9·1 kV per mm. and is claimed to have a factor of safety of $3\frac{1}{4}$.

The authors suggest on page 88 that the same temperature limits may be employed for solid cables as for any other type, as regards both absolute temperature and operating range. Do they mean by this that it is possible to exceed the values normally accepted for 33-kV solid cables which are already usually exceeded with other types? As regards dielectric loss the solid cable would seem to be definitely inferior. The remaining factor is the question of deterioration and effective life, and undoubtedly this is of fundamental importance.

I scarcely feel that the authors' work has justified their statement on page 87 that the stability of the dielectric of solid cable need be in no way inferior to that of other types. This can only be determined by long experience, whereas the statement appears to be based almost entirely on factory tests, which have been shown time and time again to be not completely reliable guides to experience in practical operation. No doubt factory tests are improving, and one appreciates the work the authors have done to develop accelerated ageing tests; nevertheless, in the past solid cables which have given trouble have successfully passed tests which at the time were thought to be extremely severe and representative of practical conditions. The authors themselves are evidently doubtful, as on page 69 they refer to the fact that accelerated ageing tests tend to force the cable maker to design against quality tests rather than against service performance. If the authors intend this comment as a criticism of tests asked for by the cable users it is somewhat unfair, because clearly the user must endeavour to safeguard himself, and if the cable makers and the British Standards Institution are unable to put forward official ageing tests for high-voltage cables the user must do the best he can.

Again, on page 68 the authors point out that further work is obviously necessary before complete elimination of solid-type cable deterioration can be achieved and also before the ideal acceptance test can be evolved, while on page 86 they refer to the fact that their work on solid cables has enabled them to appreciate the extreme sensitivity of the performance of a cable to small inconsistencies in its make-up. Finally, on page 88 the authors point out that the greatest existing need in the sphere of solid-type cable is the formulation of an acceptance test which will be truly revealing and will serve to reject cable lengths containing potential faults, failing which the cable maker is forced to adopt an exacting form of process inspection to prevent the occurrence of inhomogeneities. As they point out that the measure of his success would only be revealed in the service records of his cable in the years that follow, it is apparent that the user of such cable would be accepting a very onerous responsibility.

Even if in technical respects the solid cable will equal the other types it seems to me doubtful whether it would have any advantage in initial cost. Admittedly, oil-filled and gas-pressure cables have been more expensive in the past, but oil-filled cables have been so successful that they are likely to be cheapened by considerable reduction in insulation, and the possibility of their heavier loading further reduces the difference in cost. I imagine that any apparent difference still left would be eliminated by the necessity which the authors point out for extensive elimination of lengths of solid cable below a certain standard of uniformity.

Apart from the above considerations, one major advantage which the solid cable can never have and which oil-filled and gas-pressure cables possess is the possibility of determining the condition and pressure of the oil or gas while the cables are in operation, and so keeping a check on any deterioration of the dielectric and enabling any faulty cable to be withdrawn from service before actual breakdown occurs.

I am disappointed that the authors have put the general emphasis of their paper on the effect of their work on the improvement of 66-kV and 132-kV solid cables and have not dealt with its effect on cables for 33-kV and below. Such cables represent relatively a far greater investment by cable users, and it seems to me that the work of the authors might considerably assist in reducing the thickness of dielectric and in increasing the present low operating temperatures. In both directions very large sums would be saved to the electricity supply industry. Although on page 69 the authors suggest that it is usually commercially impracticable for operating undertakings to take the risk of trying out such improvements, I think that many undertakings would welcome any such opportunity to assist in reducing the cost of high-voltage underground transmission. This has been so in the past, and I would mention in particular the valuable work carried out on the North-East Coast under the late Mr. Charles Vernier some 20 years ago, which greatly assisted at that time in reducing excessive dielectric thicknesses and raising operating-temperature limits on 11-kV and 20-kV cables.

I should like the authors to make clear what they mean by the use on page 80 of the phrase "solid phase." I note their reasons for the choice of 0·2-sq. in. cable as the most suitable size for general testing, but I think there would have been much to be said for considering both smaller and larger sizes. On the larger sizes, in particular, troubles have been met with which have not shown up on the medium sizes.

With reference to the M.C. (single-phase) cable, it would appear that the making of the joints will be complicated and expensive and that the making of the terminations will be more so. In view of their statement that the reduction in maximum stress is distinctly limited, do the authors think that this design for 60-kV or 132-kV working is a commercial proposition?

It would also be interesting to know what happens if the insulation between the conductor and inner sheath breaks down. What I have in mind is that probably before complete failure of the insulation occurs at some point on the route, the whole of the insulation between the sheath and the outer lead will have been subjected to over-stressing, and deterioration on many parts of the route may have set in.

In the two conclusions on page 88 the authors state that under certain conditions the sealing ends and joints would be subject to vacuum and that this should be prevented by the use of a solid block in the cable insulation, or a solid joint. Surely this will mean that the more highly stressed cable insulation will then be subjected to the low pressures and therefore be liable to breakdown.

Mr. P. V. Hunter: It is quite impossible to judge of the probable performance of a highly stressed cable from any form of acceptance test which has so far been devised. What has sometimes been done in order to determine the quality of a cable from an acceptance test is to sheath it, sectionalize the sheathing, and then test each short length of cable so obtained; but that is obviously a quite impracticable method for cables for commercial sale. It is, however, the only means which I have seen proposed which would determine the quality of a cable by a test after completion. I think that we shall always have to assume that the method of manufacture has been carefully, properly, and conscientiously carried out, and that the type of cable and its performance have previously been determined by very careful life tests such as those discussed in the paper. I have been advocating this form of test for over 20 years.

The word "phantom," which the authors use to describe the currents superimposed on these cables, gives quite a wrong impression of these currents. The authors point out that to obtain the loadings which were postulated they had to pass 400 or 500 amp. through a 0·2-sq. in. cable, which is anything but a phantom current. I hope, therefore, that the expression "phantom" as applied to these circulating currents will not come into general use.

Another point on which I should like to touch is the question of uniformity and quality. It is a matter of general experience that high quality and uniformity go together, and although the authors say that uniformity is to be aimed at and is more important than the highest quality, I have never yet found a case where improvement in quality does not also give improvement in uniformity. Possibly the authors were intending to emphasize that there is a point beyond which it is not necessary to strain after quality.

In my opinion the worst possible guide to the quality and performance of a cable is its operation in service. Thus there are 33-kV belted-type cables in operation to-day which are giving perfectly satisfactory service and have done so for 10, 12, or more years; yet nowadays no one would think of making a 33-kV belted-type cable. Nevertheless, I should like to emphasize the desirability of co-operation between cable makers and supply authorities, under controlled conditions, for such co-operation may be very valuable indeed to the manufacturer. To give an indication of the kind of experiment to which I refer, 11-kV cables have been inserted in commercial 33-kV circuits, the 11-kV cables having less than half the sectional area of conductor of the 33-kV cables with which they were placed in series. (The reason why such a great reduction in the size of the conductor is possible is that no operating authority ever loads its cables fully except in abnormal circumstances; there are normally sufficient spare cables, or the conditions are such that cables in general are fully loaded only for a very short time in the year. If it is desired, therefore, to obtain any idea of the behaviour of cables on load, the worst guide possible is the performance of the cable in normal operating conditions. The normal loading of the 33-kV cables mentioned above was probably about two-thirds the guaranteed load, and this meant that there was an overload, or what would be regarded as an overload, on the test cable.) With the friendly co-operation of the supply authorities it should be possible to put in one or two lengths of such lower-voltage cable, and at the end of a year or two to remove half a length and replace it by a new and more optimistic one, if necessary, thus obtaining under practical conditions a confirmation of the results shown by the authors' long life tests.

With regard to the future of the solid impregnated cable, my opinion is that it will not be beyond the capacity of engineers, when all the conditions are fully known, to design a solid impregnated cable which will operate just as well as the makeshift cables we are now producing. For the oil-filled cable is, after all, a makeshift, as is the gas-pressure cable; they are both devices which have been adopted to eliminate certain troubles. The great difficulty in the case of solid impregnated cable is to establish the conditions under which these particular sources of trouble—ionization, gaseous discharges, and so on—are completely eliminated; in other words, to make the cable behave elastically. I do not think that the ionization results obtained by the authors in their stability test indicate that they are even approaching a complete solution of this problem.

The cable whose life-test history is shown in Fig. 4 would not necessarily be unsatisfactory in service, because it is an established fact that ionization or gaseous discharge has to exceed a certain local intensity before disruption of any kind occurs; but if one examines the ionization curve of an oil-filled cable, a gas-pressure cable, an impregnated-paper cable, or any other form of gas cable, one does not find anything like what is shown in Fig. 4, but just a line starting at and continuing level with the origin. Until solid impregnated cables achieve that desirable condition, I think very few cable engineers will be satisfied that the correct solution of the problem of very high-voltage working has been reached.

Mr. E. B. Wedmore: This paper has helped to bring into prominence the importance of ageing and of ageing tests, and on the other hand the great difficulty of developing adequate ageing tests. The word " ageing " has been objected to in some quarters on the ground that 10 years from now cables will be precisely 10 years older, no more and no less. I find that the Oxford Dictionary recognizes expressions such as " causing to grow old " and " the process of ageing." It recognizes that an accelerated ageing test may bring about something in a short time which ordinarily would take longer to bring about, and therefore we can correctly refer to " accelerated ageing " and " ageing tests."

Ageing tests present a very difficult problem. If we make an empirical test, which is the cheapest and easiest to develop, the results can hold only so long as we are using the same material, whereas all the time we are trying to alter our materials and modify our technique, thus automatically rendering our empirical ageing tests obsolete. A scientific ageing test assumes a knowledge of the properties of all the materials involved. Take such a simple case as ageing by oxidation. One can accelerate oxidation by raising the temperature, but what guarantee is there that the degree of acceleration will be the same with each of two materials, A and B? Again, there may be some material present in minute quantities which has the effect of delaying oxidation. If the standard is adopted of producing a certain amount of ageing by oxidation, by raising the temperature for some stated time, the result will depend on whether or not these other materials are there present. The material which has bad ageing properties may pass the test on account of the presence of some material which causes the commencement of the action to be delayed. This illustration indicates the difficulties of the scientific problem which has to be faced in developing an ageing test.

Fortunately, throughout the last 20 years cable makers have bought their materials in large enough quantities to enable them to be put under scientific control, whereas 20 years ago the manufacturers using paper in other sections of industry were buying very largely on the basis of price and appearance, with no ageing tests and with hardly any tests of quality. Since then standard specifications have been prepared for some of the papers more largely used in industry, but we are still struggling with the difficult problem of ageing tests.

The importance of life tests in the cable industry can hardly be exaggerated. The alternative to the cable is the overhead line, and we all know the troubles to which it is subject. If the cable maker can guarantee a good enough performance, I feel that in the future a great many more lines will be put underground.

The use of power factor as a criterion of the condition of insulation has been exceedingly valuable, but I feel that we shall hear a great deal more of high-voltage d.c. testing as a means of informing us whether the cable is liable to give trouble within a certain period. Still more, I believe that we shall hear of better methods of observing what is going on in a cable than the power-factor test which is now used for this purpose. A number of experiments in this connection have been made recently with the cathode-ray oscillograph, and these have shown considerable promise.

Dr. P. Dunsheath: I cannot quite follow the authors' arguments against burying the cable in stability tests. It seems to me that the nearer the condition of the cable during these tests approaches practical conditions under which the cable is going to work subsequently, the better it is for all concerned—both makers and users—and the more reliable will be the application of the results to the assessment of the qualities of the cable. There is, of course, no real technical difficulty nowadays in the measurement of dielectric losses on cables buried in the ground. In this connection, also, I am surprised that the authors, presumably for reasons of economy, employed a smaller type of terminal insulator for their tests than that which would be supplied for use in practice with the particular cable tested. For instance, on the 66-kV cable they used 33-kV sealing boxes. I should be interested to know how the authors fared when they submitted the results to the prospective customer; my experience is that consulting engineers expect a stability installation to be as nearly as possible identical in all respects with the suggested large-scale installation.

The authors favour the a.c. method of heating the cable while on stability test, but I think that heating with direct current is preferable where possible. Suitable machines are now available for this method, supplying large direct currents at low voltages, the whole of the machine being insulated from earth for the full voltage to which the cable is subjected in the test. The great advantage of using direct current is, of course, that it makes possible the avoidance of sheath effects, to which the authors refer on page 72. It also makes the sheath available for other purposes, such as temperature measurements, or supplementary heating by passing an additional current through the sheath under controlled conditions.

I see that on page 80 the authors, after expressing a very lukewarm support of the condemnation of calculations involving inverse roots, immediately quote the results obtained by applying a twentieth inverse root. I think they must have written the second part of that paragraph on a different date from the first part. The forecasting of long-time values by this method is, of course, quite discredited by present-day conceptions of dielectric operation.

One general criticism may be made on this paper: it does not compare strictly side by side two types of cable in which only one variable has been introduced; the results are given for two cables, but without a clear indication of the difference in result occasioned by a particular factor which applies to one and not to the other. A glaring example of this defect is to be found on page 86, concerning the use of metallized paper. The conclusions would have been much more convincing if two identical cables had been used—identical, that is, in all respects except that one had a plain standard conductor and the other a conductor covered with metallized paper. The authors also say a great many useful things about intersheaths, but nowhere do they give the results obtained on two cables, one with intersheaths and the other without.

There has been a great deal of loose talk in the last few years on the question of voids and vacuous conditions. It seems to me that there are four inter-related factors here: (1) the gaseous void or space; (2) the vacuous condition; (3) the ionization, and (4) the deterioration following ionization. The second two are occasioned by the first two, and it is because of the loose way in which the two groups are connected, (1) and (2) to (3) and (4), that there is a need to-day for some more specific consideration of this question. Uniform manufacture of the cable is desirable because of the way in which it controls the first factor, and I suppose that to some extent the second factor is also controlled by the method of manufacture. I see that on page 85 the authors confirm an important observation recorded by me in my 1933 paper* which is closely related to this question, and that is that if the lead sheath of a cable which has a very high degree of ionization be cut, and air allowed to enter the dielectric, the ionization may disappear. Another important consideration relating to this matter is that failures of these early cables nearly always took place at times of light load following heavy load. Here again, the vacuous condition comes into consideration. Further, on page 82, the authors state that low vacua can persist in a cable and be accompanied by the most complete stability. Summing up these observations then, it looks as though a cable may have a low internal pressure and may have voids, but that one without the other may not produce ionization and deterioration; danger accompanies the coincidence of these two conditions.

This suggestion is supported by the conclusion reached on page 87, where it is shown that the multi-core cable has a better resistance than the single-core cable to these deteriorating influences under the same vacuous conditions. This seems fairly easy to explain; it is a result of the simultaneous operation of two factors—the vacuous condition and the void condition. In the single-core cable when the vacuous condition obtains the voids become vacuous; in the 3-core cable when the vacuous condition obtains the voids which are vacuous are probably not in the dielectric, but in the filler spaces, and so the vacuous condition does not produce ionization. There is a clear moral to all this, somewhat on these lines: improvements in manufacture will reduce the chance of a void, but as there must always be a risk of a void in a solid dielectric there is nothing quite so certain as controlling the pressure conditions in the void by a little superimposed fluid pressure.

Mr. K. S. Wyatt: I agree with the authors that the usual acceptance tests of cable fall far short of indicating the relative values of different makes under operating conditions, and that the only way of evaluating cable at present is to subject it to some form of load-cycle test. Unfortunately, all the load-cycle tests which have so far been devised are exceedingly slow and expensive, so much so that they have only been used for studying cable deterioration and not for specification purposes.

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* *Journal I.EE.*, 1933, vol. 73, p. 321.

There are so many important variables in load-cycle ageing of cable that I think it is safe to say that by far the greater amount of work that has been done, although it has been a step in the right direction, has yielded results of very questionable value. Often terminals filled with thin oil under pressure have been employed, thus resulting in a solid cable being tested under oil-filled-cable conditions. Little attention has been given to care in cutting the sample, so that air has rushed in at the ends, or, if the temperature of the cable at the time of cutting was high, oil ran out at the ends. Unless very carefully designed terminals have been employed, leakage of compound out or of air in will occur during test, negativing the value of the results. Terminals have been used which are filled with bitumastic compound, the air bubbles in which act as a cushion to take up expansion of the compound in the cable. Unless the terminals are isolated electrically, electrical measurements during test will have no significance. Even when these pitfalls are avoided, most load-cycle procedures do not afford anything approaching a fair comparison of quality of different makes.

The work described in the present paper has avoided these pitfalls. I should like to ask, however, whether there was a complete absence of high-frequency disturbances on the cable during these tests. For example, if there are sharp points on the busbar to which the cable is connected, so that when it is inspected at night corona can be seen, it is very probable that the life of the cable on test will be appreciably shortened. It is essential in judging results to know that such conditions were absent.

With regard to basic power-factor, Figs. 8, 9, and 10 show little or no change in this characteristic with ageing, but since the measurements were made at room temperature they have little significance. Oil-paper insulation, even when badly deteriorated, may have low values of power factor at room temperature, and should be measured at not less than 60° C. Cable with copper conductor, after ageing, always shows some increase in dielectric loss of the layers near the conductor. It is unfortunate that the authors have not shown some "before" and "after" curves of radial power factor; these are most revealing.

They state that in the early cables, failure occurred by "tracking," but in the later cables "tracking" was absent. Is this not due to the fact that the later cables were more compact? Have the authors related compactness of the layer structure with life? The reason that compactness is important to life lies not only in the fact that its absence means a considerable increase in the volume of oil and hence in differential expansion effects on the load cycle, and not only in the fact (pointed out by the authors) that a loose cable gives rise to high dielectric losses at 80° C. and above owing to the pronounced conduction effects in the oil layers, but more particularly in the obviously marked stratification of the dielectric into oil and oil-impregnated-paper layers consequent upon its absence. Until recently the thickness of the inter-layer oil film and its effect on cable characteristics have been matters of dispute. Now, however, it is possible by means of the wafer method to measure accurately the thickness and distribution of these films. It is found that many normal cables possess inter-layer oil films the thickness of which is 10 % to 20 % of that of the paper tapes, while more loosely wound cables possess oil films of still greater radial dimensions. On the other hand, a compactly wound cable will have an inter-layer oil film so thin that it cannot be seen under a high-power microscope. It is a matter of common observation in post-mortems of used high-voltage insulation of composite type that at the junction between two dielectrics of different permittivity there is a more marked deterioration than at other points. This is chiefly explained by the sharp potential-drop at such junctions. Since oil has a permittivity of 2·3 and oil-impregnated paper of 4·7* there are obviously similar layer-to-layer potential discontinuities across the radius of a loosely-wound oil-impregnated paper cable, so that the oil films, having far lower electric strength than the paper, are forced to carry the greater part of the stress. These potential discontinuities, which are further affected by butt spaces and other inhomogeneities, give rise to tangential stresses along the surfaces of the paper tapes. The consequence is that tracking is made easier. Loose winding also provides easily penetrated inter-layer paths for the ionized gas stream and thus causes tracking. In a compact insulation, on the other hand, inter-layer oil films are to a great extent absent, the curve of potential gradient is comparatively smooth, and the penetration of ionized gas streams between layers is extremely difficult. It is believed that tracking and ionization breakdown only take place in such a cable under much higher electrical stresses. It is also believed that much of the published work on tracking has been done on comparatively loosely wound cables.

If the inter-layer oil-film is eliminated by increased uniformity and compactness, and a cable made up of dense super-calendared paper the surfaces of which consist of a tough, almost impervious skin, the oil content of the cable will be low and the behaviour of such a cable on the load-cycle problematical. The elimination of the inter-layer oil-film of a cable constructed of paper having a high water-soluble inorganic-salt content will result in virtually continuous fibre paths from conductor to sheath, along which conduction effects may take place. Elimination of inter-layer oil films may be expected to improve cable only when sufficient inter-fibre oil is present, and when the paper and oil are free from inorganic water-soluble salts. The increased difficulty in bending cable with compact insulation must be taken care of by properly adjusting tape tensions and by the selection of suitable widths for the tapes.

The authors refer to the greater probability of early failure on test of a long length. Is this not because there are periodic mechanically weak spots along the cable length which have their origin in the taping assembly? What is the distribution of such weak spots, and how can they be prevented; or can the authors suggest a test by which they can be located? What effect does bending during installation have on life?

A brief description of a load-cycle test now being developed in America for specification purposes and which is being used by several cable research laboratories may prove of interest. It represents an attempt to put the load-cycle test on as scientific a basis as possible, by controlling the important variables. In developing the procedure it is an inflexible rule to test all cables in duplicate, for it would be difficult to build up confidence in a procedure which would not produce, in adjacent lengths of cable, results which would agree reasonably well. Extreme care is taken in the preparation of the samples: several yards of cable near the reel end are discarded, the actual cutting being carried out either under oil or under temperature conditions such that little or no oil leaks out or air in. Special pressure-tight terminals are employed which, even with the 3-conductor design, leave little space to be filled with oil or compound after assembly. Insulating sleeves about 6 ft. from either terminal, carefully applied to prevent inclusion of air or vacuous space, isolate the terminals electrically. In order to measure internal pressure within the sheath, a specially prepared Bourdon tube gauge is wiped to the cable at one end. The length of sample may be as little as 40 ft.

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* J. B. Whitehead: *Transactions of the American I.E.E.*, 1933, vol. 52, p. 673; D. W. Roper: *ibid.*, 1935, vol. 54, p. 323.

The ageing procedure consists of 5 steps. The first is the conditioning cycle and consists in applying gradually increasing a.c. load to the conductors (in 3-core cable all three conductors are tied together, until a copper temperature of 95° ± 5° C. is reached. No voltage is applied. During the cycle, gauges are carefully watched to see that the pressure does not rise above 100 lb. per sq. in., otherwise the terminals may burst, or leakage of compound may occur. The lead sheath gradually yields, relieving the internal pressure; when the latter does not drop by more than 2 lb. per sq. in. per 24 hours the conditioning cycle is complete. This will require about 3 days. The purpose of this cycle is twofold: first, to stretch the sheath of all makes by a like amount (otherwise the well-impregnated cable, which under the normal load-cycle would stretch considerably, would compare unfavourably with the poorly impregnated cable, which, by reason of its gas cushion, would show little stretch of sheath and hence less marked ionization). The equivalent stretching of the sheath of all makes compared is the more necessary now that different types of lead are being used, resulting in widely different internal pressures at which the sheath begins to yield. The second object of the conditioning cycle is to redistribute the compound uniformly throughout the length, for during storage on a reel outdoors the compound tends to run from the top of the turns to the bottom. This results in ionization spots, making comparison of one cable which has been stored for a long time, with another more recent cable, unfair. Redistribution of compound takes place quite readily in the absence of voltage.

The second step is to subject the cable to $2\frac{1}{2}$ load-cycles with $2\frac{1}{2}$ times rated voltage, continuously applied. Load is applied for 24 hours to bring the cable to 90° C. at the conductor. The cable is allowed to cool for 48 hours.

The third step is the ice cycle. At the end of the third 24-hour heating cycle of the second period, the cable is covered with ice, and the voltage is increased to 3 times normal. The cable is kept submerged in ice for 5 days (3 days is insufficient). The object of this procedure is to create voids throughout the insulation in which intense ionization may have an opportunity of deteriorating the insulation. In this stage of the test an indication of the stability of the insulation with respect to ionization may be obtained.

The fourth step is to permit the cable to come slowly to room temperature. The voltage is then increased to $3\frac{1}{4}$ times rated voltage.

The fifth step consists in ageing the cable at room temperature with voltage only. The criteria of quality are time-to-breakdown, ionization factor, and increase in the 60° C. power factor measured at low voltage. Cables of loose mechanical assembly may show ionization factors as high as 7 %, although if the overlay of the taping is uniform they may yet have a long life. Cable with random overlay of tapes may break down in the early stages of the test. Cable of compact and uniform structure may have an ionization factor of less than 1 % throughout the test. In some cables the ionization is so great that during the fifth period of test with voltage only and no loading, the sheath temperature may reach 35° to 40° C. In general, the test appears to separate good and bad cables satisfactorily. It is, of course, still subject to modification.

The key to the behaviour of the cable on this test appears to lie to a great extent in the gas production by ionization, and the same factor may be the cause of the changes which take place under the milder test described by the present authors. Whereas the absolute internal pressure after the application of ice may drop to 10 lb. per sq. in. or less, i.e. roughly 5 lb. per sq. in. below atmospheric pressure, it gradually rises until at the end of the fifth period of the test it may reach 30–40 lb. per sq. in. with some makes. The gas is produced by ionization. If after only 1–2 days of the ice period some cables are given a conditioning cycle, the cable will be rejuvenated, the ionization factor will return to low values, and the whole ageing process appears to be reversible. If, however, the ice period has been continued until more positive gas pressures obtain, then a conditioning cycle will not return the cable to its former condition, i.e. the ageing process is irreversible. The explanation perhaps lies in the fact that if the ageing is stopped when only small amounts of gas have been produced, a conditioning cycle may distribute the gas and cause it to dissolve in the compound, and no serious ill-effects will be observed. But when greater amounts of gas have to be considered, then solution will not take place on the conditioning cycle; the ionization factor remains high, and failure eventually occurs. I believe that the gas-evolving properties of the compound which result from ionization under cable conditions are a major factor in determining whether ionization breakdown will occur. Compactness, as already discussed, is also thought to exert a decided influence on life under high electric stress. Another important factor is the designed length of " step " leakage path from conductor to sheath; this is true only where the overlay of each tape with respect to the tape beneath it is constant, i.e. when there is a sharp peak in the distribution curve of Fig. 21, as in (*a*). Where overlay is not constant, resulting in distribution curves such as the lower one in Fig. 21(*b*), the minimum leakage path may become as a result dangerously short, profoundly affecting life under ionization conditions. Although a long leakage path may be obtained by increasing the overlay to the region 40 % to 50 %, a high degree of constancy of overlay must be maintained, otherwise the cable will probably be worse, not better, with regard to life under ionization conditions. Where there are periodic mechanical weak spots along the cable length, these will determine life, but general compactness and the average length of leakage path should affect the ionization characteristics and the general tracking and deterioration along the length. In both instances it is assumed that reasonably good drying, degassing, and impregnation have taken place.

The over-voltage used in the American tests, $2\frac{1}{2}$ to $3\frac{1}{4}$ times rated voltage, appears at first extremely high in comparison with the over-voltage used by the present authors. Actually, the corresponding maximum stresses are used in the present tests because American insulation thicknesses are somewhat greater than those employed here, and because American conductor sizes are much larger, so that there is not as great a difference between maximum and average stress. For example, the maximum stress in an American 3-conductor 24-kV cable of $\frac{19}{64}$ in. insulation with conductors of modified sector shape is 0·20 kV per mm. per kV, and of extreme sector shape 0·23 kV per mm. per kV. The maximum stresses on the American test would be 7·1 to 9·1 kV per mm. and 8·1 to 10·5 kV per mm. respectively. These correspond to the values of 5 to 7·5 kV per mm. employed by the present authors.

The only sure way to improve cable is to adjust the compound, paper, and fabrication by means of the load-cycle test. The greatly improved values of maximum stress and life indicated in the upper curve of Fig. 15 show what carefully carried-out research such as this can accomplish.

Mr. E. L. Davey (*communicated*): The test results obtained by the authors on oil-impregnated solid-type e.h.t. cables are typical of such cables. After the temperature cycles have been applied, ionization occurs within the dielectric at the rated working voltage of the cables.

In their conclusions the authors suggest that the stability of sound solid-type cables need be in no way inferior to that of other types of cables. Such a statement cannot be admitted on the basis of a comparison of the results given by the authors for solid cables with the results obtained on gas-filled cables.*

The authors' definition of stability as applied to solid-type cables is apparently that the cable system with its necessary barrier joints and reservoirs at terminal ends shall not suffer a continuously progressive increase in ionization during service. This implies that the cable system shall stand up to the service voltage conditions, indefinitely, by reason of the dielectric being uniform and its thickness such that the working electric stress is below the lowest stress value of the stress/time curve for such a dielectric with a specified temperature range.

For economy, it is essential for high-voltage solid-type cables to operate at stresses which are very close to the stress value referred to above. For instance, on page 81 the authors mention 50 kV per cm. as a design value of stress, while in Fig. 15 the 1 000-day stress value is given as approximately 57 kV per cm. for 1934–35 cables. Inevitably a grave risk of service failures due to any small variation in the manufacture of the cables must exist under such circumstances.

The illogicality of attempting to press the development of solid cables is apparent when the characteristics and possibilities of the gas-filled type of cable are considered. The design basis of such cables is as follows: (*a*) There shall be no ionization up to at least twice the working voltage under any service condition. (*b*) There shall be no migration or drainage of compound within the cable system up to conductor temperatures of 100° C. (*c*) There shall be no necessity to use any barrier joints, reservoirs, or accessory apparatus, on any gas-filled cable installation. The compound/gas ratio of such cables can be, and is, adjusted so that the gas density in the region of maximum electric stress is constant under all conditions, thus ensuring complete immunity from ionization. The reinforced sheath is designed to deal with the internal gas-pressure variations, without the necessity of cold working of the lead sheath and without creep of the sheath. The design basis is such that a cable, completely stable both physically and electrically, is assured. Such cables have been in service successfully for some time now and are definitely passing out of their development stage, thus demonstrating that they are perfectly practicable.

An important feature of these cables, apart from their complete freedom from dielectric deterioration, is that damage to the sheath, resulting in an escape of gas, is indicated by a fall of pressure on the pressure gauges on the ends of the cable system. The cable system can be kept in service by feeding in gas without any harmful electrical or physical effects on the dielectric. Such conditions are in marked contrast to those of the vacuous solid-type cable system where a leak results in the sucking-in of humid air and/or moisture and the first indication of trouble is an electrical breakdown.

Gas-filled cables are economically feasible for voltages ranging from the very highest down to at least 33 kV, and their non-deterioration properties combined with their high current ratings and simplicity are features which commend them to cable manufacturer and cable user alike. The conception of the gas-filled cable arose some 6–7 years ago as a result of a realization of the physical limitations of the solid-type cable dielectric. No striking development in solid-type cable dielectrics has occurred in the meantime, and it is difficult in view of the developments in the gas-filled cable to understand the authors' defence of the solid-type cable.

When a thoroughly impregnated lead-sheathed solid-type dielectric has been subjected to temperature cycles, voids must exist on the dielectric at the lower temperatures. The gaseous pressure in such voids is of a low order, while the radial dimensions in the direction of the electric field will be at least equal to the thickness of the individual paper strips. It is futile to attempt to use such dielectrics for high voltages when other dielectrics, perfectly stable both physically and electrically, are available.

It appears reasonable to predict that in future no cable user will contemplate using solid-type cables for 66 kV and upwards.

Mr. W. F. Davidson (U.S.A.) (*communicated*): American conditions such as the general installation of cables in ducts rather than armouring and burying in the ground, and the tendency to use higher copper temperatures, naturally suggest a different answer to some of the problems considered by the authors.

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* C. J. Beaver and E. L. Davey: "The Gas-filled Cable," Paris H.T. Conference, 1937, Paper No. 204.

In their discussion of stability during ageing (Section 3.32) the authors refer to the problem that faces all investigators who are attempting to develop an accelerated ageing test—a choice must be made between the various alternatives that present themselves. In the case of cable, two principal accelerating factors are involved: the first is an increase of electrical stress, and the second is an increase of temperature—each above that anticipated for normal operation of the cable. The authors have chosen to concentrate almost entirely on the first, and it is in this choice that I would differ with them. If I were making a selection, I should give quite as much emphasis to the matter of temperatures.

Although in their Conclusions the authors state " the continued deterioration of compound is difficult to avoid," in Section (3.32) they remark that " From a purely chemical point of view it has been established that little deterioration will arise from operation at maximum temperatures as high as 100° C. provided that suitable materials are employed." My own experience has indicated that this last statement is less true than that stated in the Conclusions; in fact, we have observed a disturbing number of cases in which the dielectric loss of the insulation has increased to such an extent as to reduce seriously the cable capacity, in spite of the fact that there is no evidence of the cables ever having been operated at temperatures even as high as those for which the manufacturers designed them.

As an illustration, I would refer to a case which came to light recently in the course of an examination of circuit loadings for a group of cables installed in a common duct bank. It was found that some of these cables, although less than 18 years old, had undergone such serious deterioration that the dielectric losses at the temperature existing in empty ducts of the bank were in excess of the heat which could be dissipated from a typical duct. In other words, these 15-kV cables were useless for carrying load, and the capacity of the entire duct bank was increased by removing these cables from service. This, fortunately, was an extreme condition, but test data on many samples of 15-kV and 27-kV cable removed from service show that it is not unusual to find increases of from 6 to 8 or as much as 10 times in the dielectric losses measured at 75° C. after cables have been in service for 10–12 years, with proportionate deterioration for cable of more recent manufacture. It should be pointed out that in none of these cases has there been any evidence of severe overloading of the cable, nor any evidence to suggest that the cables were abnormal in the sense that they differed seriously from other cable manufactured at the same time and in the same factory. Our investigations have failed to disclose the fundamental nature of the changes that have taken place, but it does appear that chemical action of some sort has been largely responsible and that this is of such a nature as to be little influenced by electric stress. Accordingly, higher temperatures seem to be indicated in the choice of ageing-test conditions.

As a corollary to these comments, I should like to suggest that more emphasis might well be given to the dielectric losses measured at the higher temperatures. For instance, in Fig. 7 of the paper it is shown that the relative increase in power factor is much greater at the higher temperatures than at the lower. Since dielectric loss *per se* is generally of chief interest because of its influence on the carrying capacity, it follows that greater importance should be attached to the measurements at the higher temperature as contrasted with those made at room temperature. Furthermore, we might well recognize the human tendency to somewhat ignore changes if they appear to be small and to become disturbed by relatively large changes.

Finally, with Fig. 7 in mind, I should like to suggest some disagreement with the authors' explanation of the high losses experienced toward the ends of the test length. It seems to me rather difficult to explain the large increase as due entirely to compound oxidation, and I should be inclined to suspect that a very considerable factor was the penetration of compound from the joints and terminals.

Mr. W. A. Del Mar (U.S.A.) (*communicated*): Load-cycle ageing tests have been in use for several years under my direction for the purpose of comparing cables made with different types of paper and oil. It was found desirable to make a large number of tests of each type of cable and therefore a standard size was adopted, which would permit the rapid and economical preparation of samples. The size adopted was as follows: No. 4/0 American Wire Gauge, 19/·1055 in., having a diameter of 0·528 in.; total thickness of insulation, 0·220 in.; thickness of lead, 4/64 in. The lead was made thinner than usual in order to relieve the pressure on the ends and thus make it easier to design ends which would not leak under the alternations of high and low pressure incidental to the cycles of load. The ends were made of bias-cut varnished cambric cemented with Harvel oil-stop paint, and contained a metal-foil cone of exponential form. Tests were made at a maximum stress of 200 volts per mil (7·9 kV per mm.). The stress was applied continuously except while measurements were being made. Phantom current was circulated to give a conductor temperature of 85° C. for 8 hours per day. Cables were laid on an asbestos table in the laboratory, in a horizontal position. Up to 12 cables, each 15 ft. long, under the lead, were connected with their conductors in series, so that all would carry the same current. The total length of cable on test at one time was therefore 60 yd.

The following arbitrary limits were set, for the completion of each test: (*a*) Power factor at 85° C., 2 %. (*b*) Difference between power factor at 100 volts per mil and at 20 volts per mil, 0·5 %, at room temperature. (*c*) Hottest spot temperature of sheath, 8 deg. C. over mean sheath temperature. (*d*) Breakdown.

Upon reaching any one of these limits, the cable was removed from test, opened, dissected, and submitted to the following examination and tests: (1) Magenta tests for " wax," and general visual examination. (2) Radial power factor. (3) Tape tightness by compactness tester. (4) Examination of Styrene wafer.

In most cases the power-factor rise proved the limiting feature, and by removing cables from test before failure the character of deterioration could be best studied.

Cables made in the standard way were tested simultaneously with those on which information was desired, in order to obtain a direct comparison. When new oils or resins were the object of test, they were tested in a Nederbragt cell for stability against gassing and rise of power factor.

Power-factor measurements were made not only at a conductor temperature of 85° C. but also at room temperature, but the latter were found to be useless except for ionization measurements, as the power factor did not rise appreciably at room temperature, with ageing, even on the worst cables. This is explained by the present authors' observations to the effect that the basic power factor at atmospheric temperature is principally determined by the paper component, whereas at higher temperatures the loss becomes increasingly a function of the impregnant. As it is the impregnant which suffers the principal deterioration, it is obvious that power factors at high temperature constitute the true index of deterioration.

The paper is not quite clear about the temperature at which the power-factor measurements were made, but judging from the low values shown in Fig. 4 the measurements were made at room temperature. It is to be hoped that the authors will clarify this point.

Another matter which requires clarification is the following: The tests on cables EC58/1a and EC59/1 indicate that normal grading is superior to grading with the less dense paper nearer to the conductor. This is contrary to the authors' own theories, because in connection with their SR cable they say: " It is an essential feature of this design that the dielectric is graded so that the parts most severely stressed are formed of paper with the most highly absorptive qualities."

The time is not yet ripe for publishing the general results of the load-cycle tests made by the procedure which I have described above, but it is hoped that a description of the procedure itself may have some value in a general discussion of test methods.

[The authors' reply to this discussion will be found on page 100.]

NORTH MIDLAND CENTRE, AT LEEDS, 6TH DECEMBER, 1938

Mr. W. Dundas: The authors' suggestion of increasing the working stress in the cable dielectric with the object of producing cheaper cables presumably refers to cables suitable for voltages up to 10 kV and not beyond. That expedient is not likely to appeal to those responsible for maintaining supplies, as the importance of continuity of supply has reached such proportions that any reduction in the factor of safety appears to be a retrograde step.

The penetration of oxygen into cables when cut for jointing is a new factor to be taken into consideration. It would appear that it may be necessary to revise the present method of jointing when dealing with cables for very high voltages, and I would ask the authors whether attempts have been made to styrenate the cable near to where the joint is to be made before commencing operation, and if so, with what results.

Mr. R. M. Longman: I am interested in the multiconductor cable shown in Fig. 2, and would ask whether the fillers between the cores act as oil reservoirs and whether the arrangement gives a better heat-dispersal than is obtained with an equivalent single-conductor cable. In the Milliken cable the larger conductors are split into three or more sectors and give a better heat-dispersal than plain cores.

It is rather singular that one of the first 49·5-kV 3-core cables of the belted type lasted so long—perhaps the looser wrapping of the papers had made possible better drying and better filling, resulting in the formation of less voids after repeated heating and cooling cycles. Many of the troubles experienced with cables in the last 10–15 years are due to the fact that much larger sections of copper are now in use, 3-core cables up to 0·6 sq. in. per core and single-core cables up to 1 sq. in. being common.

Fig. 4 shows a minimum temperature of 10° C., but cables have often to work at temperatures round about 0° C., and other difficulties may be experienced at the lower temperatures. Stress or condenser cones for end-bells are mentioned in the paper, and I can confirm their value and importance. The bulk of the 33-kV and 66-kV cable end-bells in this area were originally made without these cones, but after a few failures had been experienced all were remade with the stress cone incorporated, and no further trouble has been experienced.

Mr. K. C. Coop: In the early part of the paper the authors say that they had difficulty both in installing and in carrying out tests on buried cables. The costs of the test also seem to have been prohibitive. I assume, therefore, that the majority of the tests were made on cables in ducts or on racks and that the results described in the paper are only strictly applicable to such forms of installation. Will the authors explain whether it is possible, and if so on what grounds, to correlate the results obtained with those to be anticipated from buried cables.

The authors state, in the section devoted to " Test Results," that they think it unwise to give the individual history of each cable tested, as this might lead to confusion of the issue. Is there not a distinct danger in picking out individual cables and attempting from such results to generalize as to the behaviour of the class of cable?

The title of the paper seems rather misleading, as I gather that the tests are not made at normal voltage but at an over-voltage. It is not clear from the authors' curves what was the correct figure of the applied voltage. For instance, according to Fig. 8 it would appear that a 60-kV cable was tested for 70 days at 45 kV, the voltage then being raised for a period of 30 days to 58 kV. I understand, however, from the authors' verbal summary of the paper, that the test voltage as stated is the phase-to-neutral voltage, the actual applied voltage being $\sqrt{3}$ times this figure. This represents a 45 % over-voltage, as compared with the 100 % and 200 % over-voltage applied in accelerated ageing tests.

If, with enforced tests of 100 % over-voltage the tendency is to " force the cable maker to design against quality tests rather than against service performance," at what over-voltage may this tendency be said to cease?

Mr. F. Gurney: I should like to ask the authors to give a definition of the ionization factor in terms of the power factors at the two test voltages.

It is very encouraging to find that they have confidence in the solid type of cable for voltages of 132 kV. One welcomes the possibility of removing all sorts of special installation difficulties and incidental expenses associated with various other special types of cable for this high operating voltage.

I should like to mention that, sooner or later, we may have much cheaper cables for rural electrification. I believe some single-strand cables have been produced which can be laid across fields and other suitable areas at prices which compare very favourably with those relating to overhead lines.

Mr. A. C. Bailey: I note that the end lengths of the cable specimens used for test, which are in a vertical plane, have a higher power-factor than the remainder; I suggest that this is due to the migration of the cable oil.

I note that many of the authors' breakdown tests have been carried out with direct current. It would have been preferable to have used alternating current, as the potential gradient throughout the insulation under a.c. conditions is different from that prevailing under d.c. conditions.

[The authors' reply to this discussion will be found on page 100.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 13TH FEBRUARY, 1939

Mr. E. E. Dunn: It is good to note the continued research toward the perfection of solid-type e.h.t. cables. All that can be accomplished in regard to the simplification of reliable cables and their associated accessories is well worth while from the practical point of view of the user.

With reference to the subject of potential faults, I gather from page 84 that within the cable there are invariably taking place discharges, which may persist down to very low stresses. Perhaps the authors would describe, in a little more detail, their radio method of detecting these discharges.

In the Summary, the authors state that " a relation between the over-voltage of the test and the life of the cable has been established." It would be interesting to know the form of this relationship, particularly in connection with the application of the relationship to the probability of life of solid-type e.h.t. cables which have already been in commercial use for a number of years.

There occurs, on page 78, the statement " the variation in ionization along the cable length is explicable in terms of the impregnation process, and it is reassuring to note that the service breakdowns are not coincident with the parts most severely deteriorated." Did these breakdowns occur on apparently good insulation, or were they the outcome of some of the " known defects "? I should be glad if the authors would explain this feature a little more fully. In connection with the effect, mentioned on page 73, of leakage resistance leading to inaccurate power factor/voltage curves, have the authors been successful in overcoming this by any other means than insulating the sheaths from earth?

It is stated on page 88 that " The most stable type of solid-core cable generates internal vacua over extended periods of service." This raises my final query: When long-established solid-type cables are opened for the purpose of, say, route diversions, is the unavoidable breaking of the vacuum likely to cause ultimate failure due to the formation of air pockets distributed throughout the adjacent insulation?

Mr. W. A. Cook: There are two points in the paper to which I should like to refer. Firstly, the authors mention in the Summary that a relation has been established " between the over-voltage of the test and the life of the cable." To what extent is that relationship a definite one? Fig. 15, which appears to be the main evidence for this relationship, is entitled " Trend of improvement in e.h.t. cable manufacture." Whilst the curves in this Figure do show a distinct trend, it seems somewhat doubtful whether they show a definite relationship, because it would appear that a number of alternative curves could be drawn with the points shown. Moreover, it presumably cannot be assumed that all the cables represented on one curve had the same quality of manufacture.

From the theoretical point of view it would appear quite possible that one cable, which showed very severe ionization at, say, 25 % over-voltage, might show none at working voltage; whereas another cable having slight ionization at 25 % over-voltage might show very little less at working voltage. So that whilst the life of the first cable at 25 % over-voltage might be less than that of the second, the life at working voltage would be greater. In the case of condenser insulators such a state of affairs is certainly possible, and a judgment of an insulator at an over-voltage is therefore not necessarily a true judgment of it at working voltage. I should like some further information with regard to this point.

The other point is the reference on page 84 to the fact that discharges in cables can be heard by the unaided ear or by a sensitive radio-receiver. I am not quite sure whether the authors intend to indicate that these discharges occurred during their tests, or that such discharges occur in cables actually in service. In the latter case, have they discovered any method for distinguishing between a degree of ionization under which cables can successfully operate and a degree of ionization which may be harmful?

Mr. J. M. Kellas: To what extent have the authors found that bending tests and general handling interfere with the high standard of manufacture aimed at on the larger sizes of cables tested?

They quote evidence of the migration of compound from the ends of a section of cable towards the centre, and attempt to show that if suitable precautions are taken this does not materially affect the stability of the cable. As practically no cable route is level, have any tests been carried out where there is a considerable difference in level between the ends of cable sections? How far is such a gradient likely to modify the authors' results?

It would appear that the solid cable for higher voltages (66 and 132 kV) aimed at will be of unwieldy dimensions. I would refer in particular to the 132-kV cable for which results are given on page 78. This cable has a radial insulation thickness of 1·0 in., whereas the corresponding size of oil-filled cable has a radial insulation thickness of 0·63 in. In addition, the overall dimensions would be still further increased by the special core construction used.

Further, for such high voltages, in order to make a cable of reasonable dimensions, a higher operating stress than 4·5 kV per mm. is necessary. According to Fig. 15, an ageing test has been carried out at a maximum of 5·6 kV per mm. on a cable designed to work at 4·5 kV per mm. This shows a factor of safety of only 24 %, which would hardly satisfy an operating engineer. Have the authors any further evidence that higher operating stresses than those quoted can be used with safety on solid cables?

Compared with other researches on high-voltage cables, one might suggest that the authors have been tackling the problem the wrong way round. Instead of compensating for and overcoming the known changes which take place in a cable, they are endeavouring to prove that, if special precautions are taken, such changes do not affect the satisfactory life of the cable.

Mr. H. Parry: I take it that the radial power-factor tests mentioned on page 75 were made on papers not actually in the cable itself, but taken out of the cable.

I suggest that it is possible that the power factor of the cable when loaded is not necessarily the same as the value observed when the temperature is uniform throughout the cable.

As a result of the recent modifications of the Schering bridge it may be possible to measure the power factor of cables under load. If the authors have done this, will they let us know their results?

Mr. J. Dickinson: The height to which electrical potential can be economically raised depends upon the available insulation. If there were no insulation the free electrons, which constitute the current, would escape to earth without doing any useful work. Hence an important function of the insulation is to assist in leading the energy to the apparatus which is to transform it into useful work.

There is, however, the much more important function to be performed by the insulation, that of transmitting the energy to the point where it is to be applied, as shown by Prof. Poynting in 1884. The metal conductor does not transmit any energy. All energy entering the conductor is lost in it as heat. The conductor is not strained by the flow of energy around it, since the whole stress is borne by the insulation, which is electrically strained as a result. This may be appreciated more fully by remembering that it is the strained part of a system that transmits the energy. Hence, the insulation is the energy carrier.

In view of this argument I should be glad if the authors would show that a "phantom" load, such as they have used, does really reproduce the important conditions obtaining in practice, by actually employing the dielectric as the energy transmitter.

It would appear that failure in cable dielectrics should at least be a function of the amount of energy actually transmitted. This point does not seem to be referred to in this paper, and I feel that it is probably a serious omission.

Mr. E. C. I. Macdonald: The authors' multi-conductor cable, described in Section (2.21), appears to be a somewhat expensive form of construction, and the cost, judging from the details given, is rather out of proportion to the maximum possible stress reduction of 10 % which is quoted. How do the authors propose to joint this cable? Will the three conductors in each phase be bunched at the joints, or will they be kept separate and the intersheath screens maintained through the joints?

I suggest that the means adopted by the authors for heating the cable under test, described on page 72, is hardly a fair method of providing the necessary temperature-rise, as in service the heat is produced almost entirely in the copper. Will not the temperature gradient in the cable under the test conditions, with the authors' method of heating, be different from the temperature gradient in service; and consequently, will not the behaviour of the compound in the cable on test differ from that in service?

Will the authors explain further their statement on page 82 regarding the rate of deterioration in winter as compared with that in summer? Is it their experience that the maximum core temperature attained by fully loaded cables at, say, the winter peak is actually lower than the maximum core temperature at the height of summer with, probably, a lower loading?

Owing to the small scale of the authors' life-history diagrams it is difficult to see the actual shape of the load-cycle curve. Did the cycle consist of a steady load switched on for a specified period, during each 24-hour period, or was the load varied to simulate a typical system load curve? I suggest that experience shows that the cyclic variation in loading on cables due to the shape of the average load curve has more effect on the life than any given steady load. The point is interesting in view of the statement in the Introduction as to designing a test plant to reproduce the conditions under which the cable operated.

The authors refer to the urgent necessity for devising some acceptance test which will serve to reject cable-lengths containing potential faults. One of the greatest difficulties in formulating such a test is that if it is to be of any value it must show up incipient faults or weak spots in a given cable-length before the length is aged, otherwise there is a risk of cables passing the acceptance test and subsequently failing in service.

Mr. W. A. A. Burgess: The authors make only a brief reference to compound expansion, a question which has engaged the serious consideration of supply authorities and switchgear manufacturers in respect of terminal sealing-bells and trifurcating boxes. It is appreciated that there must always be a dilation of the normal impregnating media, and my experience is that it manifests itself at terminal points, where breakdowns have been definitely traced to it. It is indicated in various ways, namely by the cracking of a terminal box, by the expression of compound through box joints, and more frequently by the existence of voids in the box compound round the crutch, where the cable cores are spread, due to the cable oil or compound having expanded and displaced the box compound under load conditions and having contracted again under temperature conditions at which the box compound is not sufficiently fluid to follow it.

From the manner in which they treated the cables referred to in the paper, I gather that the authors regard styrenation as a universal cure at all junction points. Although styrenation may be all that it is claimed to be as an insulating barrier joint, yet expansion and contraction within the cable have to take place; and while the authors' tests would appear to show that the cable is capable of dealing with its own expansion and contraction problems within a fairly wide temperature range, a definite lead is required from the cable makers before the switchgear manufacturers can demand styrenation to protect them from cable compound expansion. I should be glad to see a statement from the authors as to the expansion of a normal cable compound, in cubic inches, at the end of a standard drum-length cable for a range of temperature between 0° C. and 85° C.

The alternative to styrenation, from the point of view of the manufacturer and the user, in terminal boxes and similar devices, would appear to be the use of a box compound of the same nature as the cable compound. Such a compound might, however, give rise to other troubles arising from cracking at low atmospheric temperatures, or from absorption of moisture at higher atmospheric temperatures; or again, if the compound were of the vaseline or semi-fluid type, it might permit water drops to pass slowly through it, all of which would eventually lead to the type of fault already experienced, and get us no further. I should like the authors' opinion on this subject.

I am disappointed to find in the paper no mention of tests or data in respect of the temperature of cables under actual short-circuit conditions. I refer to conditions met with on a 6-kV system, where the short-circuit capacity on a major switchboard may be at least of the order of 500 MVA, and the corresponding symmetrical short-circuit current of the order of 50 kiloamp. These current conditions at 6 kV and higher voltages are by no means unusual in the supply industry, and I have yet to find evidence of a cable breakdown within close proximity of the switchboard (and therefore presumably unlimited by the effect of conductor impedance)* in which either the conductor has been destroyed or the paper has been carbonized beyond a matter of inches from the actual fault.

In a paper of this nature I should have expected some reference to the maximum conductor temperature allowable without causing permanent destruction to the insulation. This is a matter of vital importance to the supply industry, since the data contained in the Cable Research Handbook appear to indicate that temperature-rises of the order of 500 deg. C. per sec. are possible on a cable as large as 0·25 sq. in. subjected to a current of 50 kiloamp. and that a cable as small as 0·06 sq. in. would have a temperature-rise of the order of 8 000 deg. C. As far as I can see, however, these figures do not take into account the increased value of the temperature-rise per sec. due to the increase in resistance of the conductor with increase of temperature. The value obtained for the 0·06-sq. in cable would cause it to blow as a fuse in much less than 1 sec., while the temperature-rise of the 0·25-sq. in. cable would indicate definite charring of paper insulation within 1 sec.

In spite of this, there are a large number of such cables installed throughout the country to-day, and liable to be subjected to such currents. The supply authorities concerned are naturally wondering whether there is not a cooling effect which has not yet been investigated, or at least not yet been reported, which safeguards their cables up to periods extending to some 2–3 sec., which is the limit imposed by graded overcurrent protection on certain systems; or whether they have been merely lucky in the past and may expect a future fault of this nature to practically destroy a complete length of cable as distinct from a very short piece. The authors' views on this subject would be much appreciated.

Prof. J. C. Prescott (*communicated*): One or two points in the paper require, I think, further elucidation; for instance, what is the nature of the stress/life curve (page 69, middle of col. 1) upon which is based the choice of the stress to be employed during the ageing test? Again, on page 78 in the case of the 132-kV cable, how was the voltage applied in this case? It appears from the figures given at the top of page 80 that a single-phase voltage was used between the cores and the sheath. Is this a satisfactory arrangement when the cable in service would be used on a 3-phase supply?

There is one other point which occurs to me and that is in connection with Fig. 1, where the voltage of a high-voltage transformer is shown as being measured by a voltmeter connected to a tertiary winding. The cable loop presumably constitutes a load of considerable capacitance, and one would expect that the voltage of the transformer would therefore rise above its e.m.f. when connected to the loop. Thus, while the tertiary winding would indicate the e.m.f., the voltage actually occurring at the high-voltage terminals might be considerably greater than this.

THE AUTHORS' REPLY TO THE DISCUSSIONS

Messrs. T. R. Scott and **R. C. Mildner** (*in reply*): Replying to Mr. Beard, we are in agreement that further data must be advanced before a strict comparison is made between solid-type cables and the other types (referred to later by Mr. Hunter as " makeshift cables "). Among other things it will be necessary for corresponding test data from long-period ageing tests on these other types to be produced for comparative purposes. It should be remembered that the solid type of cable is the basic cable and that the other types are solid-type cables to which have been added certain devices tending to minimize ionization. Thus the oil-filled cable is a solid type with ducts and external reservoirs to compensate for oil expansion and with the unfortunate requirement of an oil of low viscosity. The pressure cable is a solid type of cable working in a high-pressure atmosphere confined in a pipe or the equivalent thereof. The gas-filled cable is a solid-type cable with part of the impregnating compound replaced by high-pressure gas. If our tests had shown that the fact of the distension of the lead sheath of a solid-type cable during load cycles and the resultant introduction on cooling of incomplete impregnation within the sheath accompanied by vacuum or low pressure was the sole or chief limitation to the economic design of high-voltage cables, we would immediately admit the futility of spending money on research on solid-type insulation for cables at 60 kV and 132 kV. Our tests have indicated clearly, however, that cables can have pronounced ionization factors and yet behave satisfactorily in service. For example, Cable No. E.C.72 has a pronounced ionization factor within the ageing test-voltage range, and yet, at the date of writing, it has completed 514 days at stresses ranging from 6 kV per mm. at the commencement, stepped up to 6·6 kV per mm. at 108 days, to 7·2 kV per mm. at 200 days, and finally to 7·5 kV per mm. at 365 days. It would appear to us from similar results already recorded that this cable will not fail at this stress as the result of ionization effects. Further, it is believed that a similar cable can now be designed and manufactured to surpass this performance. We think that this type of result is one of the most significant arising from this series of tests. Equally significant and applicable to all types of cable is the phenomenon illustrated in Figs. 5, 6, and 7, i.e. the tendency for the power factor at higher temperatures to increase with ageing. We have a tribute to the importance of this aspect in the contribution provided by Mr. Davidson, who gives temperature limits priority over stress limits, and quotes the importance of the effects noted at voltages as low as 15 kV and 27 kV. We would reiterate that there are at the moment insufficient published data on long-period ageing tests on the various types of cable to justify forecasting the eventual superiority of one type of cable over other types. We cannot accept that accurate estimates of "factor of safety" can be formulated unless such results are analysed, and we question whether it is really scientifically correct to use such a term. Mr. Hunter indicates in his contribution some of the difficulties encountered in assessing the minimum conductor size and insulation thickness capable of meeting the load requirements of any given underground transmission line. Nor can we admit yet that the provision of means for checking the working of the devices incorporated to minimize ionization is of necessity a certain safeguard against the progress of all types of deterioration which may lead eventually to breakdown.

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* See *Journal I.E.E.*, 1938, vol. 82, p. 488.

A further argument in support of the testing of solid-type cables is the effect of such development work on cables at lower voltages. We would refer again to Mr. Davidson's contribution and would also point out that in Great Britain, during the period occupied by the tests described in this paper, the permissible temperature-rise of 30-kV and 60-kV cables has been increased by over 50 %; insulation thicknesses have been reduced on 60-kV cables and will probably be similarly reduced on cables for lower voltages. We would draw attention to the results obtained on E.C.62/1, which indicate that we have covered the range from 10 to 132 kV.

It is our experience that in modern cables it is safe to deduce design data from long-period tests on a stress basis, and that the radial insulation thickness of the cable under test is relatively unimportant. The results obtained, therefore, on 60-kV cables, which are in the majority in our work, are directly applicable to cables of all voltages.

We agree that it would have been ideal to cover a range of conductor sizes, but some limit had to be imposed on the scope of the research, and, after due consideration, it was decided that the difficulties introduced by the adequate loading of large conductors outweighed the probable gain in experience. It was assumed that large conductors, whatever mechanical difficulties they might introduce, behaved similarly to medium-size conductors in respect of the types of deterioration under study. On the other hand, small conductors were believed to introduce impregnation difficulties, and therefore some small-size conductors were included.

We would hasten to assure Mr. Beard that in no way do we criticize the factory acceptance tests asked for by cable users. The fact is that at least one type of defect is not shown up by acceptance tests; whether this type of defect leads to breakdown in service or not depends on an aggregation of circumstances. Hence it is not safe to work any type of cable up to its full possible working stress. We find, however, that if an ageing test of the type described indicates a satisfactory performance at a stress of over 7 kV per mm. it is safe to work in service at 5 kV per mm. all cables of a manufacturing consignment which closely resemble the cable tested as described: hence our call for uniformity in manufacture.

The term "solid phase" is used to indicate the paper lapping structure which is the fixed part of the dielectric, as compared with the migratory impregnating compound.

With reference to the M.C. cable, we would state that a simple and effective joint is available. The utility of the M.C. design will depend largely on the stress value at which it is eventually found possible to work the cables. The design is of course applicable to all types of cable and is not confined to the solid type. A simple arrangement can be introduced to trip out the cable as soon as the voltage of the intersheath "wanders" from its designed value. This protective system has the added advantage that it eliminates the "bump" to the system which usually results from a cable breakdown.

Mr. Beard's final comment appears to ignore the fact that all solid-type cables when off load develop vacuum or low pressure in the insulation. If the "solid phase" is properly constructed and the impregnation is good, no harm results. In many types of joint and termination, however, the "liquid phase" alone comprises the insulation in the region of maximum stress. Under low pressure this "liquid phase" is electrically very weak. It is therefore axiomatic to avoid vacuum in joints and terminations, unless sound paper reinforcement equivalent to the cable insulation has been applied therein.

With the majority of Mr. Hunter's contribution we are in complete accord. The term "phantom" refers of course to the load on the cable rather than the current, and was adopted from telephone-cable engineering, where it is used to describe a circuit superimposed on another circuit without addition to the number of conductors.

We are in agreement with Mr. Wedmore that in due course some standardization of cable-ageing must arise. We would point out, however, that separate ageing tests under standardized conditions are applied to the compound, to the paper, and often to the impregnated paper. The object of the present series of tests was to obtain an overall check on the finished cable to obtain some idea, among other things, of the relation between material tests and cable performance.

Dr. Dunsheath is correct in stating that there is no fundamental objection to tests of the type described being carried out on buried cables. After experience on cables on racks in air and buried underground we standardized on cables in troughs, mainly on the score of accessibility and temperature control. It is desirable to be in a position to reach, in winter, temperatures lower than those obtained at, say, 3 ft. underground. Dr. Dunsheath in this and in his insulator query appears to overlook that these tests were conducted mainly as a scientific investigation into cable behaviour and not as commercial tests for customers. Since the terminals were sealed off from the cable by styrene joints the only risk we took was that electrical discharges in the end-bell might adversely affect the cable insulation—a phenomenon to which Mr. Wyatt refers. It may be that such discharges have an appreciable adverse effect on the cable performance, but it is our feeling that, in view of the fact that such conditions are liable to be encountered in service, these discharges should appear as an essential feature of the ageing test.

We agree that the use of direct current for heating the cable has certain advantages in cases where it is desired to test 3-phase cable with single-phase over-voltage. On the other hand, the flexibility of the a.c. method of heating and the very possibility of controlling the sheath losses by the disposition of the cable-run represent advantages which the alternative method lacks. We have no rooted technical objections to the adoption of the d.c. method.

We would wholeheartedly condemn the application of the inverse power law to the calculation of long-period breakdowns from short-time breakdown results by extrapolation of results. Our application of an inverse power law is perfectly defensible as a convenient statistical method of reducing to a common basis the results of long-period ageing tests at a series of voltages raised in small steps. The particular power value selected was based on average curves obtained on a large number of samples tested over a range of stress which amply embraces the stresses for which adjustment is required. We think, for example, that the life history of E.C.72 as quoted above to Mr. Beard can be reduced by the inverse power law to an equivalent number of days at, say, 6 kV per mm. Further investigation is necessary, but we see a clear distinction between the two uses of the inverse law.

We cordially support Dr. Dunsheath's analysis of the void-vacuum-ionization condition, with the exception that when he refers to a void within a cable we would substitute "void within the insulation." Thus a single-core cable with distended sheath may have voids within the cable sheath but yet not within the cable dielectric. In the case of 3-core cable the chances of the void occurring outside the insulation are increased: hence the better average performance of the 3-core type.

Mr. Wyatt refers to the desirability of eliminating the inter-layer oil film. We would suggest that he really means the reduction of the thickness of this film to ultra-microscopic dimensions—a state to which he refers earlier in his contribution. We can foresee that bending and other difficulties might occur if the film were totally eliminated.

Secondly, we would refer him to our objections (page 68) to the American type of accelerated ageing test, which he describes in an amplified form. Mr. Wyatt indicates that the test requirements of $2\frac{1}{2}$ and $3\frac{1}{4}$ times working voltage at present result in stress values which do not differ greatly from the values we are now reporting, e.g. 7–8 kV per mm. If, however, the American cable makers reduce insulation thicknesses and raise the working-stress value we do not think they should be asked to meet tests scheduled up to 17–20 kV per mm. It is admitted that if accelerated ageing tests are to be carried out in a short period of time the conditions must be made severe enough to aggregate in a short period of time the deterioration normally effected in a period of years, but the difficulty is to strike a happy mean between service conditions and conditions which inevitably force breakdown in a few hours.

Likewise, cables may be able to work satisfactorily up to some maximum temperature less than 90°–95° C. and yet not be able to produce acceptable results on the type of test described by Mr. Wyatt. It appears to us that if a batch of cables were subjected to the American type of test there would be a likelihood of rejection of not only the really bad cables which would fail in service, but also of a number of satisfactory cables, leaving only the superlative cables as survivors. If it is claimed that our type of test is too slow and expensive it may be considered that the American test should be used but with several samples of each cable available, so that if failure occurred under the most severe conditions the test might be repeated under less stringent conditions, and this reduction in severity might be repeated in steps until the quantitative quality standard of the cable in question is evaluated. This suggestion is, of course, made from the point of view of the cable maker who is anxious to build up the quality of his cable by changes in design, materials, manufacturing processes, etc. We note, for example, that Mr. Del Mar in his contribution describes tests carried out at 85° C. and 7·9 kV per mm. Doubtless he would propose to increase the severity of the tests as soon as he was satisfied with the performance under these initial test conditions.

We disagree with Mr. Davey's view that all research work and development work on other types of cable should be discontinued in view of the entry of the gas-filled cable into the commercial field. We think that the best interests of both cable users and cable makers will be served by careful cataloguing of the performance, economics, and other characteristics of all possible types of cable, so that choice of a cable for any specific transmission line can be made on a sound engineering basis. We feel that the best basis for assessing the performance of any type of high-voltage cable is the result of long-period ageing tests in conjunction with searching laboratory tests on both new and aged cable.

We are very interested in Mr. Davidson's contribution, especially in respect of the firm stand he takes with regard to the importance of tests at high temperatures. We would point out in partial defence of our own attitude that the American requirement of transmitting maximum kVA through existing duct lines is not a normal requirement in this country. The allocation of importance as between stress and loading capacity is therefore somewhat different. At the outset of the tests, some 10 years ago, we catered for a temperature-rise which was almost double that specified at that time, but events have shown that we ought to have aimed higher, and arrangements are being made to extend the temperature range.

With regard to the possibility of working cable insulation at 100° C., we would point out that in recent cables in our tests there is little sign of " oxidation " deterioration in the cable except at the ends, and that even this is reduced to a small value by taking due precautions during manufacture and by using joints of the styrene type which have no gas cushions or compounds of a differing type. It is perhaps true that " oxidation " can occur even in the absence of gaseous oxygen, but it appears to be possible to avoid the use of compounds susceptible to this form of deterioration.

The analysis in detail of the results obtained on cables Nos. E.C.58 and E.C.59 cannot be dealt with in this paper. The data were included merely to illustrate the type of information obtained by tests of this type and to underline the fact that breakdowns do not necessarily occur at the points of highest ionization or deterioration.

We cannot agree with Mr. Dundas that it is a retrograde step to reduce the insulation thickness of cables when tests of the type described by us prove that it is safe to do so. The process of cheapening e.h.t. cables by decreasing their size is continuously proceeding and is in fact urged on the cable makers by cable users in all parts of the world. The paper deals with cables for voltages from 10 kV upwards. Below 10 kV the problem is more one of mechanical structure and strength than of electrical deterioration.

Any precaution taken in jointing e.h.t. cables to prevent the ingress of air is certainly advantageous. Styrenation in its normal form is hardly suitable, but it is hoped that a modified form may be developed to meet this point.

The design of the M.C. cable shown in Fig. 2 is founded on a stress formula such that the thickness of insulation around each " sub-conductor " is proportioned to the size of conductor and the total thickness of insulation in terms of the well-known logarithmic stress law. In the case of the Milliken cable referred to by Mr. Longman the design problems are electromagnetic rather than thermal, and the thickness of insulation between sub-conductors is of minor electrical importance. Also, of course, no screen or intersheath is required in the Milliken cable. We consider that the fillers between the screened cores do contribute to the efficiency of the cable, but we are not quite sure of the reason for this.

We cannot subscribe to the view that the loose wrapping of the paper tapes can improve the performance of a cable, and we feel that the explanation of the results quoted by Mr. Longman with reference to early 49·5-kV cable must be sought elsewhere.

We would refer Mr. Coop to our reply to Dr. Dunsheath with regard to tests on buried cable. As far as ageing tests and deterioration analysis are concerned there is no difference between cables laid in troughs and buried cables, except that in troughs we can at times reach temperatures round 0° C. which would be unobtainable on buried cables. We can therefore increase the severity of the tests and make them representative of conditions of cables in ducts and air, and also of buried cables, in other countries. We discontinued the testing of cables in air and on racks for the reasons given on page 82 (see Fig. 16). Having obtained the temperature-range value over which it is safe to work a cable, we can convert this into current capacity for any type of laying in terms of the well-known researches of the Electrical Research Association published from time to time.

The test voltages recorded are all single-phase and can therefore be converted to 3-phase voltages by the use of a multiplying factor of $\sqrt{3}$.

It is probable that Mr. Coop's queries regarding overvoltage have been practically answered by Mr. Wyatt's detailed description of the American accelerated test and our comments thereon. In Fig. 15 we have drawn some stress/life curves which illustrate the reduction in breakdown value with the duration of the test. Taking the 1929–30 cables we could have made accelerated ageing tests at $2\frac{1}{2}$ times working stress (say 10 kV per mm.) and achieved breakdown in less than 2 days: at 25 % overvoltage we obtained a life of the order of 1 000 days and could estimate that a working stress of 4 kV per mm. was a practicable proposition. If we arbitrarily fix the minimum requirement for the short-time test at any period in excess of 2 days we should only be able to record failure and not be able to make any constructive proposal for a safe working stress. We attempt to find the voltage or stress which the cable will withstand without failure for a period of long duration; the " overvoltage " factor is then arbitrarily determined by the selected working stress of the cable. Actually E.C.47/10a, the cable referred to, was purposely raised to a voltage which would induce breakdown round about 100 days and so aid the determination of the form of the stress/life curve. On the other hand, a 60-kV cable made to-day would probably withstand 58 kV for at least 500 days, and we should have to increase the voltage quite appreciably to ensure breakdown at 100 days. We maintain our claim that long-period tests at lower voltages are more useful to the cable maker in assisting him to design for service performance, i.e. for long-period life.

We welcome Mr. Gurney's support of our contention that there is a considerable field for solid-type cables in the range 10 to 132 kV. The ionization factor in all cases is the difference in dielectric power factor between measurements taken at a high voltage and at a low voltage. Thus, for example, if the power factor at 75 kV is 0·4 % and the power factor at 15 kV is 0·3 %, the ionization factor is 0·1 % (15 to 75 kV).

Mr. Bailey's contention regarding the effect of migration would probably be correct for cables working in service under the conditions described, at least so far as power factor at high voltage is concerned, i.e. ionization factor. It might also be true of " oxidation " deterioration in which air or different-type compound migrated into the cable from the termination. In our tests the vertical run was in general sealed off from the cable under test, so that migration from the termination is not the sole reason for the phenomenon.

Mr. Dunn appears to have misunderstood the paragraph on page 84. When ionization is taking place and spark discharges are occurring in the cable under test they can be heard by the unaided ear and located in position along the cable length. If they are very faint they can be heard by using a radio receiver, but in this case it is impossible to obtain accurate location.

It is impossible, unfortunately, to construct a stress/life curve for any given cable unless the cable is divided up into a number of sections which are tested similarly except in respect of applied voltage. It is, however, possible by using different stresses on different cables to obtain a series of points indicating breakdown at various times, so that an average stress/life curve is constructed. We would refer Mr. Dunn to our reply to Mr. Coop. Over-voltage testing with alternating voltage will not give an answer to the problem of determining the life of a cable in service except in so far as the removal of a portion of the cable from service and the application of tests similar to those recorded in Fig. 12 gives an approximate answer.

The " known defects " were, in general, lapping defects and, when these are present, failure may occur at such spots in preference to more highly deteriorated spots. The fact that the thoroughness of impregnation has varied along the length, or the fact that air has entered at the ends, does not make breakdown occur inevitably in these regions of inferior quality if a serious lapping defect has occurred elsewhere in the length. A " serious lapping defect " must be evaluated in terms of the voltage or stress applied; it does not follow that it would cause breakdown at the service voltage or stress; it does, however, cause in general a serious deviation from the normal stress/life curve.

There are well-known alternative methods for compensating for leakage effects in dielectric-loss measurement, most of them being effected by modifications of the bridge circuit, but the simplest method of elimination is the insulation of the sheath.

Mr. Dunn is correct in his assumption that care should be exercised in cutting solid-type cables which have been in service for some time and which are being diverted or similarly modified. There is a danger of ingress of air, with consequent stimulation of ionization and deterioration. It does not, however, follow that breakdown will inevitably occur as a result of this.

In reply to Mr. Cook we would state that we do not base our conclusions entirely on Fig. 15, as can be seen from our reply to Mr. Coop. With experience of a large number of tests, however, it is possible to estimate that a certain range of stresses will cause breakdown in approximately 10 days, 100 days, and 1 000 days respectively, and these forecasts are fulfilled within reasonably narrow limits. Within that time range the curve of a batch of cables of approximately similar manufacture is therefore reasonably well established. The characteristic curve is only established, it is true, provided the batch of cables have a reasonably high degree of uniformity in manufacture; hence our claim that uniformity of manufacture and of test results, in terms of factory acceptance-tests, is a primary requirement.

While it is desirable that every effort should be made to eliminate ionization, our results show that ionization *per se* does not necessarily bring about breakdown, although it does produce deterioration and weakening of the cable insulation. Two cables with similar ionization factors over different voltage-ranges, e.g. 15 to 40 kV in one case and 15 to 50 kV in the other are not uniform and may be expected to show different degrees of deterioration after life testing, but there is no evidence that either will fail in service if the service voltage is chosen so that the weakening effected by this deterioration does not reduce the strength of the insulation to a point where breakdown is inevitable.

The audible discharges referred to occur whenever ionization occurs, and they persist so long as the ionization persists. If a cable removed from service shows visible signs of deterioration, it follows that audible discharges have occurred over some period of service. Naturally, in over-voltage tests the phenomenon is more common.

If it were possible to estimate the duration of life from the ionization factor of the cable it would not be necessary to make ageing tests; the results of ageing tests only go to show that the ionization factor *per se* is a very poor guide.

In reply to Mr. Kellas, bending tests are applied to cables to check the degree of distortion and damage effected by a severe bend, and in practical installations care is taken that all bends which occur during handling and installation are less severe than that applied in the bending test. In our ageing procedure the cables have been installed in circumstances corresponding to difficult conditions, particularly in the later tests, where the cable has to be pulled with severe reversed bends over the parapet of a building about 30 ft. high. Generally speaking, the cable design is perfectly adequate to withstand this treatment without diminution of quality.

No data regarding the behaviour of cables on gradients have been included in this paper, for the reason that the problems investigated are sufficiently complicated without the additional factors of resistance to fluid flow and hydraulic head being introduced. Following hydraulic measurements on cables, however, and applying therefrom rules regarding the application of stop-joints at selected positions, the test results of this paper have been applied successfully to 60-kV cables on extremely severe gradients; the cables have behaved satisfactorily.

The expression " unwieldy dimensions " is somewhat qualitative, for a 132-kV cable is naturally a single-core cable and, even if of the solid type, is no more unwieldy than, say, a 33-kV H.S.L. 3-core cable; it is less unwieldy than a 60-kV H.S.L. 3-core solid cable which we have manufactured and installed with complete success. In comparing oil-filled cables and solid-type cables dimensionally it is important not to forget the space occupied by the oil duct and any necessary protective coverings; and, in congested urban districts, due weight must be given to the total space occupied by both types, including space for joints, oil reservoirs, etc. On the question of stresses and factors of safety we would refer Mr. Kellas to our reply to Mr. Beard.

Mr. Parry is correct in his assumption that the power factor on load is, or can be, different from that at equivalent conductor temperature but with no temperature gradient across the insulation. We are afraid, however, that we cannot quote comparative values; these would in any case be different for every cable in which the radial power-factor curve, taken as Mr. Parry assumes, was of different shape. Radial power factors are usually measured at 60° C., this temperature being arbitrarily chosen as the one likely to give the most informative results.

Mr. Dickinson has raised a very interesting point. He cites Poynting's theorem to question the very foundation upon which the whole edifice of the accelerated ageing of cables is based. In view of the known variation of electric strength exhibited by materials in strong magnetic fields, it is reasonable to assume that the variation of energy strain might well affect pure electrical breakdown. But for cable insulations such breakdowns occur at peak stresses of not less than 120 kV per mm. and so are far removed from the deterioration phenomena, with which we are concerned, at stresses of 5–9 kV per mm. In our ageing tests the application of potential to the conductor of the cable reproduces in the dielectric conditions which result in certain behaviour not greatly different from the dielectric behaviour when energy is being transmitted: the loading current which constitutes the phantom load is merely a device to establish certain physical conditions within the cable, and to produce approximately but reasonably accurately the thermal gradient which will occur in service. The results obtained are therefore claimed to be a practical reproduction of service conditions. From the practical point of view this has been checked by removing cables from service and studying their deterioration characteristics in contrast with cables aged by life tests. There are, of course, important differences in the actual breakdown effects according to the energy conditions pertaining.

We agree with Mr. Macdonald that at first sight the M.C. cable appears to be an expensive form of construction. The design has, however, special applications in cases in which high working voltages are involved, and the ordinary type of design introduces a maximum-stress value which is greater than that considered safe for the cable in question. It has to be noted that the design is applicable to all types of cable and is not restricted to solid-type cables. In the case of the 132-kV solid-type cable where large values of insulation are involved and where comparatively large increases of insulation are required to effect a 10 % reduction in maximum stress, the question of cost becomes important; also we appear to get a gain in quality from the presence of the fillers.

The joint can be made by bunching the cores if desired, but preferably it is made by reproducing a screened 3-core cable lapped joint, similar, for example, to that of a 33-kV "H"-type cable, screening this joint and thereafter making any standard type of single-core joint.

Mr. Macdonald's query regarding the use of sheath circulating currents is actually answered in the sentence following the one he quotes (page 73). It is surely permissible to bring the sheath temperature up to a value which would be a service value in the case of buried cable. The behaviour of the compound is accordingly representative of that occurring in buried cables.

The reference on page 82 to greater deterioration in winter than in summer refers to our experience in ageing tests, and is explained by the fact that when the cable is off load, but still under voltage, its temperature is lower, the contraction of the compound is enhanced, and void spaces within the sheath are increased in volume. It might apply also to cables under certain conditions in service where the peak winter loads, coupled with reduced ambient temperatures, subject the cable to daily variations of temperature of greater range than are encountered with the low peak values and high ambient temperatures which obtain in summer. The life-history diagrams in the paper only indicate the daily maximum and minimum temperatures, i.e. the temperature range for the day. They do not show the temperature/time characteristic. The loading procedure is given on page 73. We agree that cyclic variations of the load have an important bearing on the life, but we claim that no more severe condition can occur in service than the application of full load for a period of the order of 8 hours followed by an immediate fall to "no load" with the cables in troughs exposed to atmosphere. It is true that several load cycles may be necessary before the lead sheath is distended to its final value, but this is relatively unimportant when a large number of heat cycles are included in the test.

Mr. Macdonald half states the difficulty of devising an acceptance test; it must reveal defects which will cause failure even if no deterioration occurs in service, and it must also reveal defects which will only become of importance if deterioration occurs.

Mr. Burgess puts up a very difficult problem for solution; before the specific quantitative query postulated could be answered it would be necessary to have many further details concerning the length of cable in question. If the cable were laid approximately horizontally, the switchgear manufacturer would only have to deal with the excess oil arising from the thermal expansion of compound situated in a few yards of cable adjacent to the switchgear. The exact number of yards, and hence the volume of compound to be dealt with, depend on the hydraulic resistance of the cable per unit length, the viscosity/temperature characteristic of the compound, the resistance of the sheath to distension, or otherwise, the stress/time/distension characteristic of the sheath, and the shape of the load curve. Approximate values can be given for the various types and sizes of cable—hence the general success of joints and terminations in service. Occasionally, however, local conditions cause serious deviations from the normal values and the phenomena described by Mr. Burgess are experienced. Gradients of course aggravate these conditions.

The use of cable compound in the box is of course desirable from the point of view of the cable, but from the point of view of the phenomena described by Mr. Burgess it would probably involve in many cases redesign of the switchgear box.

The detection of the value of short-circuit current which sets up deterioration in the cable insulation such that breakdown eventually, but possibly after a long period, occurs is an extremely difficult measurement. Until this part of the problem is solved it is difficult to state the relative effect of currents of the order of those quoted by Mr. Burgess.

We would draw the attention of Prof. Prescott to the general relationship between stress and life which we have determined for the various classes of cable considered (see Fig. 15). All the tests reported have been carried out with single-phase voltage applied to screened cable. Inasmuch as we have endeavoured to maintain conductor and sheath temperatures at a level rather more elevated than occurs in severe practical conditions, we feel that this arrangement is quite satisfactory.

With reference to our use of the tertiary winding for the indication of output voltage, we have of course determined its accuracy for different conditions of load. On no-load and at full voltage, the voltage indicated on the tertiary winding is approximately 1·5 % high, whilst with a capacitance load equivalent to 60 % of full load the indication is 2·7 % low. We have therefore judged the design of the tertiary winding to be satisfactory and sufficiently accurate for normal usage. Where extreme accuracy has been required we have of course employed alternative methods.

ELECTROLYTIC CONDENSERS

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SUMMARY

The paper deals with the development of the electrolytic condenser which is now so widely used in modern radio receivers and in amplifying apparatus.

A brief historical survey is given to indicate the lines of development which have led up to the modern designs. This is followed by descriptions of the construction and chief electrical properties of the various types of condensers which are now used. These properties influence to a very great extent the manner in which the condenser can most economically and usefully be employed.

Various theories have been put forward to explain the action of electrolytic condensers, but some of these do not now appear to be adequate. A critical summary is given, with an expression of views as to the most likely explanation.

The manufacturing methods are treated at some length, together with the considerations which influence the employment of these condensers in various practical applications. A standardized method of test is recommended to secure uniformity in assessing their properties.

CONTENTS

(1) Introduction.
(2) Historical Survey.
  (*a*) Electrolytic condensers with solid (oxide) films.
  (*b*) Polarization condensers.
(3) Theories of Operation.
  (*a*) Polarization cells.
  (*b*) Film theories.
  (*c*) Molecular structure of the film.
(4) Development and Manufacture of the Aluminium Electrolytic Condenser.
  (*a*) Present-day types of electrolytic condensers.
  (*b*) Pre-forming of aluminium anodes.
  (*c*) Assembly and impregnation.
  (*d*) Ageing and testing.
(5) Condenser Characteristics.
  (*a*) Capacitance.
  (*b*) Leakage.
  (*c*) Electrical losses.
  (*d*) Service life.
  (*e*) Dependence of condenser properties upon conditions of measurement and use.
(6) Practical Applications.
  (*a*) In rectified a.c. circuits.
  (*b*) For direct connection to d.c. supplies.
  (*c*) For use in pure a.c. circuits.
  (*d*) "Regulating" condensers.

CONTENTS—*continued*

(7) Acknowledgments.
Bibliography.
Appendix. Standard Specification for Performance and Acceptance Tests.

(1) INTRODUCTION

Electrolytic condensers have come into general use only in the last decade, as the result of intensive commercial development. Their beginnings, however, can be traced back at least three-quarters of a century. For years chemists and physicists have been experimenting with various types and speculating on the theory of their operation, but it is the interest of the electrical engineer which has led to recent advances in the manufacture and utilization of electrolytic condensers.

Aluminium and certain other metals—such as vanadium, niobium, bismuth, antimony, and, notably, tantalum—can be used to construct this type of condenser. The clean metal itself cannot be made *per se* into a condenser, but it is necessary to "form" it, i.e. give it a layer of dielectric upon its surfaces, before it can function satisfactorily as a condenser. This "forming" process is usually carried out by electrolysis. The development of much improved means of effecting this "forming" process (or "pre-forming" process, as it should more correctly be termed) constitutes in fact the major portion of the recent advances that have been made in the practical manufacture of these condensers.

Many different varieties of such condensers have been made, but considerations of size, cost, and constancy have made aluminium electrolytic condensers practically universal. Apart from short references to other types, this paper will, therefore, deal almost entirely with the characteristics and uses of various types of aluminium condensers.

If an aluminium anode is immersed in a solution of ammonium borate, for instance, and connected to a d.c. source through a variable resistance, the initial current will be that determined by the resistance in the circuit. Gradually, however, the aluminium will "form" up and the current will decrease. If the resistance is varied to keep the current constant, the p.d. across the cell will vary with time in the manner shown in Fig. 1.

At a certain point A the aluminium anode will be covered with sparks, and above this sparking voltage the rate of increase of p.d. will fall. After a further rise to the point B, the p.d. will become stationary. If a voltage higher than this breakdown value is applied, the

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resistance of the cell breaks down and electrolysis takes place in the normal way.

This formed anode constitutes the foundation of the electrolytic condenser. The two "plates" of the condenser are: (i) the anode, (ii) the electrolyte in contact with the outer surface of the formed film. The cathode in the condenser serves only to provide contact with the electrolyte, and from this point of view the actual material of the cathode is unimportant, so long as it is an electrical conductor.

(2) HISTORICAL SURVEY

Early work on the development of electrolytic condensers can be considered under two headings—(*a*) solid-film and (*b*) polarization-cell condensers. Of these, the second is now of historical interest only.

(a) Electrolytic Condensers with Solid (Oxide) Films

Wheatstone[*] is usually referred to as the father of the electrolytic condenser, but his studies in 1855 on the position of aluminium in the Voltaic series do not show up any curious phenomena. It was Buff[†] in 1857 who first observed that an aluminium anode in dilute sulphuric-acid solution was able to resist the e.m.f. of nine Bunsen cells. Twenty years later Beetz[‡] experimented with various forms of aluminium electrodes and with the oxide film thereon.

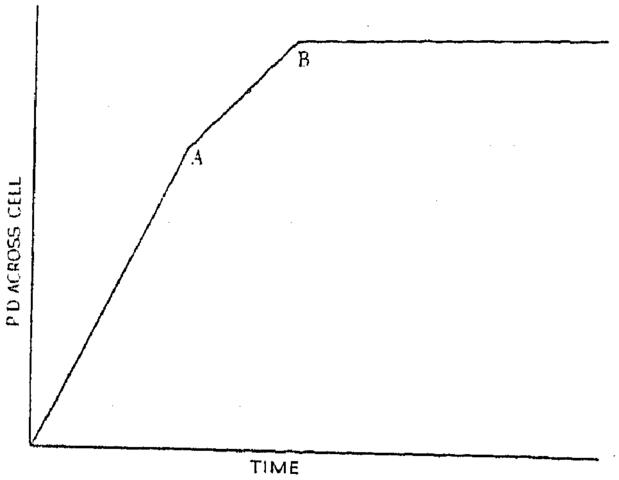

Fig. 1.—"Forming" characteristic of aluminium cell (Güntherschulze).

A = sparking voltage. B = breakdown voltage.

Oberbeck (1883)[§] and Streintz (1887)[||] thought that this oxide film might form the dielectric of a condenser with the anode and electrolyte as the two "plates," and measured the capacitance of such condensers. Other early workers of which mention may be made were Wilson,[¶] Graetz,[**] Pollack,[††] and Nodon.[‡‡]

(b) Polarization Condensers

The other type of electrolytic condenser—now generally known as a polarization cell—is usually considered to date back to investigations made by Cromwell Varley.[§§] Having need of condensers of very large capacitance, he used platinum plates immersed in sulphuric-acid solution. He was not, however, the first to utilize such devices, since he wrote, in 1860, "Prof. Jacobi of Russia has for many years used on the line between St. Petersburg and Moscow, plates of platinum in sulphuric acid at the ends of the line." These were used to give a discharge current in the opposite direction to the battery current, and were therefore functioning as condensers.

Sheldon, Leitch, and Shaw[*] have shown that the capacitance of this type of condenser varies with voltage as shown in Fig. 2, Curve B. Curve A shows a similar curve for one of Varley's condensers.

Commercially, this type of condenser has been little used since Varley's time. One form was patented in Germany in 1902,[†] and there are two types known in France[‡] but not used to any great extent. The low breakdown voltage necessitates the use of several cells in series for ordinary working voltages, while even at voltages well below the breakdown value the cell passes a large leakage current of several milliamperes.

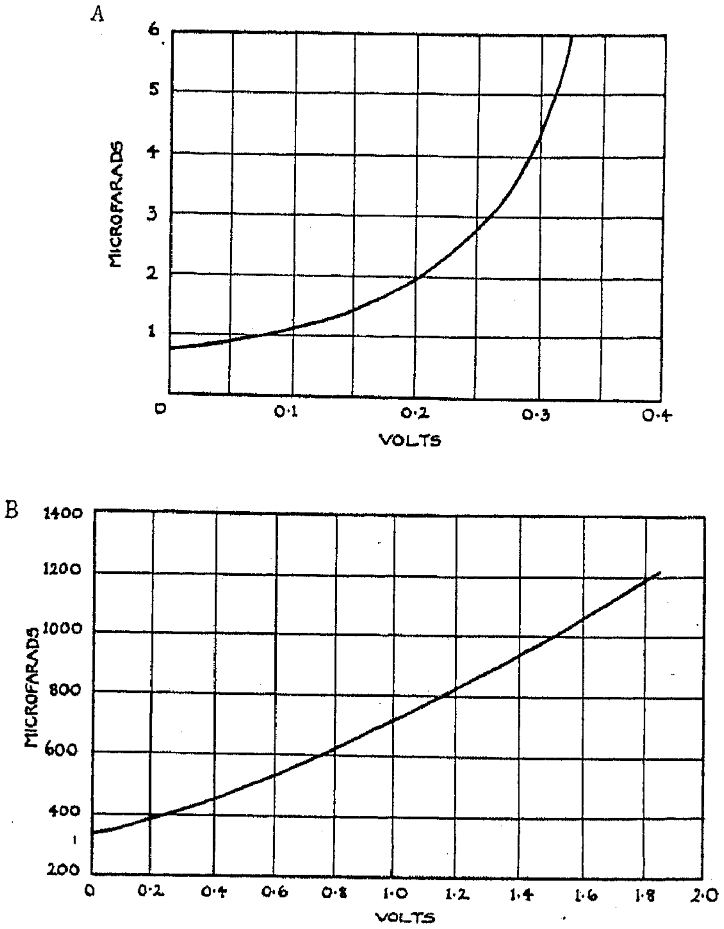

Fig. 2.—Dependence of capacitance upon voltage applied to polarization cell.

A. Cromwell Varley
B. Sheldon, Leitch, and Shaw.

Mention may be made here of a colloid condenser described by Nodon.[§] The plates are two foils of aluminium and magnesium separated by an insulating porous material with the interspaces full of a paste made of sesquioxide of iron mixed with glycerine.

(3) THEORIES OF OPERATION OF ELECTROLYTIC CONDENSERS

It is not easy to extricate the early literature on aluminium electrolytic condensers from that on aluminium rectifiers. It is probable that there is some connection between rectification and capacitance at the rectifying layer, as the so-called " dry " or barrier-layer rectifiers have shown this capacitance effect.

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[*] See Bibliography, (1). [†] *Ibid.*, (2).
[‡] *Ibid.*, (3). [§] *Ibid.*, (4). [||] *Ibid.*, (5). [¶] *Ibid.*, (6).
[**] *Ibid.*, (7). [††] *Ibid.*, (8). [‡‡] *Ibid.*, (9). [§§] *Ibid.*, (64).

[*] See Bibliography, (15). [†] *Ibid.*, (63). [‡] *Ibid.*, (17). [§] *Ibid.*, (18).

(a) Polarization Cells

The polarization condenser is the true electrolytic condenser. With two similar electrodes the condenser is symmetrical as to polarity. The maximum breakdown potential can be calculated theoretically, and the highest possible value is about 3 volts.

Varley[*] tried to visualize the electrolytic or gas condenser as an electrostatic one, and calculated that with a dielectric constant of about 1 the thickness of the layer might be as small as 10^{-10} cm., which is smaller than atomic dimensions. The easiest way is to look at the capacitance as the effect of a counter e.m.f. due to polarization.. The thickness of the dielectric has no more physical significance here than in a synchronous condenser.

Kohlrausch (in 1872)[†] formulated the equation of an electrolytic cell with a polarization coefficient P which is identical with $1/C$ in circuit equations dealing with a condenser. It was seen from this that the effect of polarization is to produce electrostatic capacitance in the cell. Later theories due to Wien,[‡] Warburg,[§] and Neumann[||] show that the phase angle of P will lie between 0 and 90°, and its most probable value will be about 45°.

Warburg[¶] predicted that the capacitance of this type of condenser would vary inversely as the square root of the frequency. Merritt[**] found that this is true at audio frequencies, but between 0·5 and 4 Mc./sec. the capacitance varies inversely as the frequency. This is presumably due to the fact that Warburg's postulate of instantaneous ionic equilibrium no longer holds good when the rate of change of voltage is made sufficiently large.

Streintz[††] was probably the first to observe that the " polarization of aluminium " was different from other forms of oxygen-polarization. He was able to get aluminium electrodes to polarize at 30 volts while no other electrodes showed any effect in excess of 3 volts. He postulated that the aluminium polarization was due to a condenser with aluminium-suboxide dielectric which had metallic aluminium on one side and the electrolyte as the plate on the other side.

Scott[‡‡] published results of capacitance measurements on a platinum polarization condenser and an aluminium condenser at different voltages. Within a range of 0·2 volt to 1 volt the platinum cell showed a variation of 10 to 1, while the aluminium cell varied about 25 %. These experiments have led to the conclusion that the oxide type of condenser (e.g. aluminium and tantalum) is not analogous to a true polarization cell. The principal points of difference may be summarized as follows:—

(i) There is a visible oxide layer on the anode of the aluminium condenser.

(ii) The aluminium anode has to be "formed." A symmetrical aluminium cell may be formed to act as a condenser with the polarizing voltage in one direction. On reversal of the voltage the condenser breaks down and has to be re-formed in the opposite direction. A true electrolytic cell with symmetrical electrodes exhibits no polarity.

(iii) The capacitance of polarization condensers increases progressively with increase of voltage. At the breakdown point, of course, the capacitance may be said to be infinitely large. If the polarization voltage is reduced, the capacitance drops at once. With an oxide condenser, formed at a certain voltage, a drop in voltage has little effect on capacitance. Over long periods Siegmund[*] found a slight *increase* in capacitance.

(iv) The leakage current of polarization condensers is much greater than that of an oxide condenser. This factor is only a corroboration, and by itself would not constitute a proof.

Electrolytic polarization has not been entirely discarded by Godsey,[†] and his reasons will be dealt with later.

(b) Film Theories

The fact that there is a visible film on the aluminium anode was noticed long ago, and extensive speculations as to its nature can be traced.

Beetz found[‡] that of the oxygen evolved during the forming process (by Faraday's law) only about 5 % went to form the film. He concluded that the film was either a hydroxide or an oxide of aluminium. Norden[§] showed the film to be $Al_2(OH)_6$.

In more recent times Sutton and Willstrop[||] analysed the film by removing the metallic aluminium with chlorine. They found that drying at 1 200° C. produced no change in weight, and therefore assumed that the film was an oxide film, not a hydroxide.

Burgess, Claasen, and Zernike[¶] have also analysed the film and found it to be Al_2O_3, and X-ray analysis confirms the presence of γAl_2O_3.

There is no doubt that this solid film is capable of acting as a dielectric. Dry condensers have been made with aluminium-oxide dielectric. Such condensers, however, exhibit little or no polarity, though Wilson[**] found greater stability when the oxide-coated plate was the anode.

A theory capable of explaining the mechanism of an electrolytic condenser must, however, go further. It must also recognize the inherent asymmetry and so correlate with the theory of the electrolytic rectifier. Oxide-film condensers with electrolytes also exhibit larger capacitance per unit area than the dry film itself.

Norden[††] adopted the solid-film theory and assumed that rectification was due to solution of the film at certain points when the aluminium is the cathode, and re-formation of the film in the next half-cycle. Considering the fact that electrolytic condensers and rectifiers are operative at comparatively high frequencies, this theory is inconsistent with the appreciable time required to " form " a new aluminium anode.

(i) Gas-film theory.

Guthe[‡‡] postulated that the rectifying action was due to a gas layer between the anode and the oxide film. This theory is now regarded as untenable, one objection being that a reduction in the polarization voltage would cause the gas to expand, and so reduce the capacitance. In practice, Güntherschulze found a slight increase.[*] Slepian[†] has also pointed out that conduction can only take place by electrons emitted by the aluminium as cathode. In a layer of gas with a dielectric constant approaching unity it is difficult to see how the work function can be lowered sufficiently for electrons to be emitted at ordinary temperatures. Godsey[‡] failed to find any variation in capacitance up to a pressure of 1 500 lb. per sq. in.

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[*] See Bibliography, (10).
[†] *Ibid.*, (11).
[‡] *Ibid.*, (12).
[§] *Ibid.*, (13).
[||] *Ibid.*, (14).
[¶] *Ibid.*, (13).
[**] *Ibid.*, (16).
[††] *Ibid.*, (5).
[‡‡] *Ibid.*, (26).

[*] See Bibliography, (24).
[†] *Ibid.*, (20), (27).
[‡] *Ibid.*, (3).
[§] *Ibid.*, (28).
[||] *Ibid.*, (29).
[¶] *Ibid.*, (30).
[**] *Ibid.*, (6).
[††] *Ibid.*, (28).
[‡‡] *Ibid.*, (31).

(ii) Permeable-membrane theory.

In the various versions of this theory, the first assumption is that there are two layers—an inner layer of oxide which acts as the dielectric of the condenser, and an outside porous membrane which accounts for the rectification.

Taylor and Inglis[§] showed that rectification is obtained by a layer of aluminium hydroxide on platinum. Cook[||] and Charters[¶] agreed that hydrogen ions penetrate the membrane more easily and thereby carry the unidirectional current.

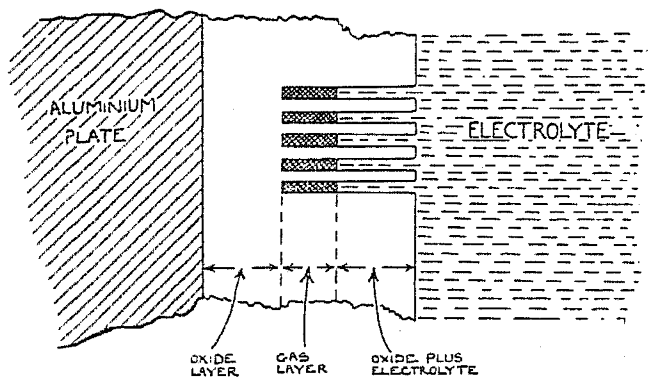

Fig. 3.—Diagrammatic representation of porous film structure (Güntherschulze).

Güntherschulze, who has probably devoted more time to the study of electrolytic rectifiers than any other worker, first brought out his theory in 1909, and developed it subsequently. His idea of the film structure is shown in Fig. 3.

Taylor[**] published a similar theory at about the same time. His theory of rectification was that when the aluminium is the cathode it gives off free electrons, but when it is positive the electrolyte has no free electrons to give. The inner film is not dependent on the electrolyte, and so the capacitance remains the same in different electrolytes. With fused salts this film gets thicker and the capacitance per unit area diminishes.

Müller and Konopicky[††] assume that the gelatinous hydroxide layer is negatively charged and therefore adheres to the anode. The electrolyte is expelled by cataphoresis when this electrode is made the anode, and the reverse action takes place on reversal of the voltage.

Dobias, Kramp, and Lebedinskaya[‡‡] put forward another theory of rectification wherein electro-osmotic displacements of the electrolyte occur in the pores of the insulating solid film. In the forward direction there is direct contact between the electrolyte and the metal, while in the reverse direction the system behaves as a condenser of variable capacitance. This theory is interesting in that it takes into account the influence of the viscosity of the electrolyte on the action of the rectifier and condenser.

(iii) Solid-film theories.

Taylor[*] in 1909 first tried to account for the behaviour of the aluminium electrolytic cell in terms of the oxide layer only. He observed no deterioration in the cell with time, and suggested that the oxide skin would account for the capacitance effect, and that the valve effect arises when electrons are emitted by the oxide acting as cathode.

Slepian[†] considered all the available data and theories and put forward a comprehensive solid-film theory. His chief objections to the semi-permeable membrane and gas-film theories are the following: First, a gas film with a low dielectric constant and lack of structure cannot lower the work function sufficiently for electrons to escape from the metal at ordinary temperatures. Secondly, an aluminium-hydroxide film lacks free electrons, while electrolytic ions could easily escape from an aqueous solution. Thirdly, the rectifying property persists if electronic conductivity is added to the solution. Thus when a mixture of lampblack and sulphuric acid is used, the electrolytic rectifier still functions without the evolution of any gas.

Slepian's theory is that the aluminium anode is covered with a solid film of high dielectric constant. This has the effect of lowering the work function. Thus if $\kappa = 13$, the work function may be lowered to about one-tenth of the normal value, and so the aluminium anode will have appreciable emission even at ordinary temperatures. The ordinary (leakage) current is kept low by space-charge effects, but at breakdown electrons formed in the film pass large currents.

In more recent papers, Güntherschulze[‡] himself has discarded his older theories and attributes both the capacitance and the rectification to the solid oxide layer in tantalum, aluminium, and certain other metals. The dielectric constant of precipitated Al_2O_3 is found to be 12·6, but after sintering this falls to 7·7 and the density rises to maximum. This is considered to correspond to the anodic layer.

(iv) Adsorbed-liquid theory.

The present authors are of the opinion that a theory of operation based on the solid film alone is inadequate, for the reasons already stated. Godsey[§] has more recently put forward a theory that the normal film in an electrolytic condenser (aluminium or similar metal) is of a greater total thickness than the effective film. The effective film maintains itself in repair by new growth wherever leakage currents flow. Water or other solvents from the electrolyte saturate the film and so increase the effective capacitance (water having a dielectric constant of about 80). A high dielectric constant keeps the film sufficiently thick to reduce materially the voltage gradients.

A rigid examination of the various theories is of interest only to the physical chemist. For the purposes of the present paper, Godsey's theory when read with those previously put forward appears to give a good physical idea of the process which goes on.

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[*] See Bibliography, (32), (33).
[†] *Ibid.*, (34).
[‡] *Ibid.*, (20).
[§] *Ibid.*, (35).
[||] *Ibid.*, (36).
[¶] *Ibid.*, (37).
[**] *Ibid.*, (38).
[††] *Ibid.*, (39).
[‡‡] *Ibid.*, (40).

[*] See Bibliography, (38).
[†] *Ibid.*, (34).
[‡] *Ibid.*, (41), (42), (43), (44), (45), (46).
[§] *Ibid.*, (20).

Godsey attaches great importance to polarization capacitance, which he thinks occurs in the outer layers of the film saturated with the electrolyte. The authors have found that the polarization effect, i.e. change of capacitance with the value of impressed alternating current, is small and can be accounted for if it is assumed that the dielectric has a hysteresis curve of the shape shown in Fig. 4.

A Q/E curve of this shape will give an increase in effective capacitance as the amplitude of the alternating e.m.f. is increased.

(c) Molecular Structure of the Film

Lilienfeld and others* have studied the anodic layer and are of the opinion that the dielectric layer consists of a larger number of polar molecules. In a well-formed condenser these molecules are properly oriented and the leakage is low. On idling, the layer is disorganized, and the excessive leakage current on applying a voltage occurs while the reorganizing is taking place. There is therefore only a very small change in capacitance owing to idling, and the law of chemical equivalents cannot be applied to the current used in the process of re-forming.

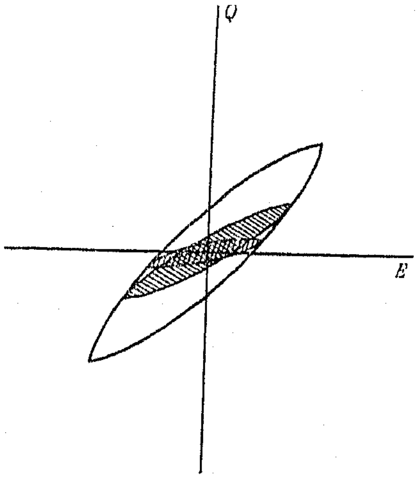

Fig. 4.—Hysteresis loops for dielectric film.

(4) DEVELOPMENT AND MANUFACTURE OF THE ALUMINIUM ELECTROLYTIC CONDENSER

(a) Present-day Types of Electrolytic Condensers

The developments of electrolytic condensers that have taken place during the last few years, while necessarily based upon then existing knowledge, have been on quite a different scale from the earlier ones. The main impetus was provided by the needs of radio-receiver manufacturers for condensers to smooth the rectified currents used in mains-driven receivers. Such needs were for condensers of several microfarads' capacitance having as small a size as practicable, which could be used on circuits of 400 to 500 volts maximum voltage, and which could be produced more cheaply than the equivalent paper-dielectric condensers. These developments, while they have taken place in many laboratories in different countries,† have followed only three main lines, and two of these differ but little from each other. These three types are generally known as the (i) wet or aqueous, (ii) semi-dry, (iii) dry or hard-dry.

As is evident from this nomenclature, the distinction is by no means a hard-and-fast one, but one form merges into another, depending mainly upon small differences in the chemical constitution of the electrolytes. In the laboratory the line of development has been in the above order, and the initial commercial uses have necessarily followed the same lines; but later commercial usage has in some cases—notably in the United States—jumped largely from one type to another and back again, governed mainly by "fashion" or by commercial interests not directly related to the technical merits of any particular condenser.

The above designations obviously relate to the electrolytes used in the condensers; but the transition from (i) to (ii) and (iii) is accompanied by a constructional change also. All the condensers have necessarily an anode carrying the dielectric film and determining the capacitance of the condenser by its effective area—whether natural or artificially augmented by mechanical or chemical roughening—and a cathode which may be the container itself when it is metallic, or be a metal sheet or foil, generally of commercial-grade aluminium. When the electrolyte is a thin liquid as in the "wet" types, the anode generally has a rigid construction, either in the form of a fluted or grooved rod, or in the form of a spiral, corrugated, or pleated strip of stiff foil of sufficient thickness to be self-supporting from a central anode post (Fig. 5). A separator layer of perforated rubber or celluloid is frequently used between the anode and cathode in such condensers in order to avoid any risk of contact between the two electrodes.

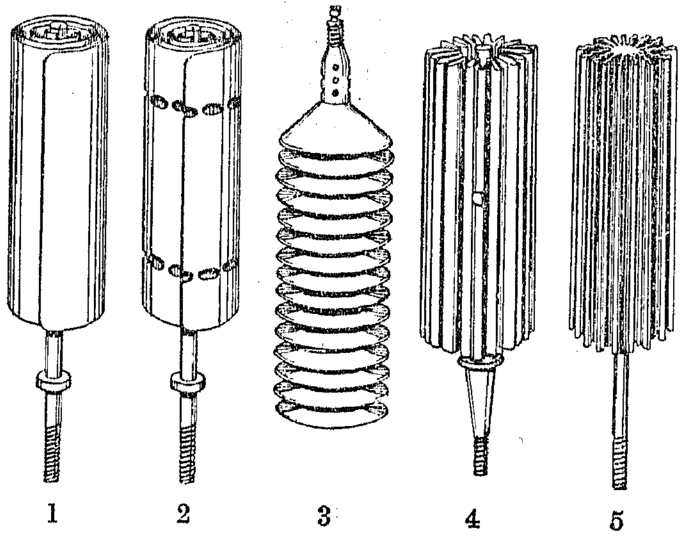

Fig. 5.—Some forms of anode used in wet-type electrolytic condensers.

1. Spiral. 2. Perforated spiral. 3. Grooved rod. 4. Star-shaped folded strip. 5. Extruded rod with corrugated fins.

With the drier types of condensers, comprising the two groups (ii) and (iii) above, the separator customarily provides the mechanical supporting means for the two electrodes, which then take the form of thin aluminium foils of 0·002 in. to 0·005 in. thickness laid up with the separator layer and wound up together into a roll. With these condensers the separator consists of one or two layers of cotton gauze or of absorbent paper, which are impregnated with the electrolyte.* By winding the two electrodes together in this way the resistance of the current path through the electrolyte between them is reduced, resulting in a condenser with a lower power factor† (Fig. 6).

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* See Bibliography, (47), (48).

† See, for example, Bibliography, (51) to (61).

The modes of formation of the dielectric film on the aluminium anode naturally differ as between one manufacturer and another, but in all cases some pre-forming of the dielectric is carried out before assembly of the condenser, followed by a final forming and/or ageing process on the complete condenser, and often also on the individual sections of which it is built up in the case of a condenser " block." When etching or other processing is employed to increase the capacitance for a given bulk of condenser, this process must precede the pre-forming [see Section (5)(*a*)].

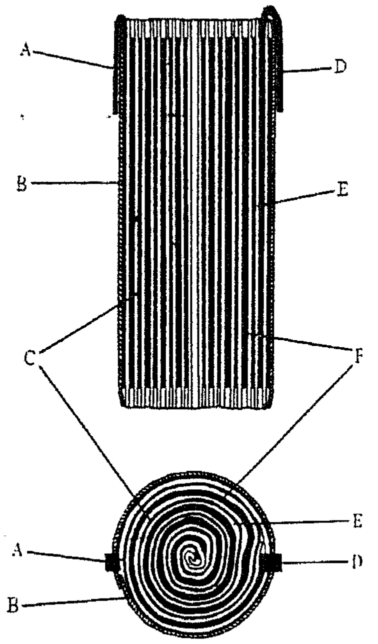

Fig. 6.—Sectional sketch of rolled dry-type electrolytic condenser.

A. Negative tab. B. Section wrapper. C. Unformed cathode. D. Positive tab. E. Separator. F. Formed anode.

(b) Pre-forming of Aluminium Anodes

This process may be carried out in one of two main ways: (i) by the discontinuous process, wherein each anode, or group of anodes, of final finished shape is subjected to an individual pre-forming treatment in an electrolyte bath;‡ and (ii) by the continuous process wherein a continuous strip of aluminium foil is subjected to pre-forming treatment in one or more stages.§

Method (i) is almost always adopted for wet-type electrolytic-condenser anodes, which, as shown in Fig. 5, customarily consist of spiralled or folded strips of aluminium,|| or of specially extruded shaped rods of aluminium,¶ which for forming purposes are assembled in a rack whereby they can be hung into the bath and forming current applied until the desired voltage is reached across the film. Control of the forming action is effected either by connecting a resistance in series with the supply circuit, or by controlling the supply voltage, as by field control of a motor-generator, whereby the applied potential is raised gradually to the full value.

Sometimes also a similar process is employed for pre-forming strips of aluminium foil, which have been previously cut to the desired length for winding up into dry electrolytic-condenser sections. More usually, however, a continuous pre-forming process is found to be a more economical one for these condensers.

In Method (ii), the continuous pre-forming process, one or more strips of aluminium foil are passed over rollers through electrolytic baths; the appropriate connections are made to pass forming current through the baths, the aluminium being the positive electrode so that a dielectric film is built up on it.* This forming process is sometimes carried out in a single stage, but more usually it is subdivided into two or more sections so that the film is built up more gradually. This arrangement gives a more stable type of film.†

The electrolytes used for the pre-forming process, whether a discontinuous or a continuous one, customarily are solutions of sodium or ammonium borate;‡ although sometimes, particularly with multi-stage forming, an addition of a proportion of a polyhydric alcohol—usually glycerine—is also made.§ With multi-stage formation an alternative arrangement includes the use of a low-voltage formation in an acid solution of considerable conductivity (such as chromic or sulphuric acid) for the first stage, to put down a porous base film which has good adhesion to the metal foil,|| into or on to which the hard high-voltage film is subsequently built up.

(c) Assembly and Impregnation

In the case of wet-type condensers the subsequent manufacturing process is mainly one of mechanical assembly of the anode posts into the outer container, the filling of the latter with electrolyte, and its closure and final ageing and testing. With dry-type condensers there follows, after the pre-forming of the dielectric film, the manufacture of the section from the cut lengths of formed positive and unformed negative foil which are wound up with interleaving separators of cotton gauze, absorbent paper, or some equivalent material.¶ This separator is impregnated with, and acts as, a carrier for the working electrolyte of the condenser.**

The semi-dry condensers have electrolytes consisting of alkali glycero- or glyco-borates in solution in glycerine, ethylene glycol, or other polyhydric alcohol, together with a small quantity of water. The dry condensers have such an electrolyte thickened into a stiff paste, by the addition either of boric acid or of similar weak film-forming material to such an extent that a mass of fine crystals permeates the electrolyte when it is cooled down to atmospheric temperature after manufacture;†† or by the addition of some colloid such as gum, which assists the formation of a gel with the solution.‡‡ The impregnation of the separator with electrolyte is sometimes carried out before or during the winding operation of rolling the foils and separator together on a winding machine; and is sometimes a distinct impregnation process applied to the rolled section. In either case its object is to obtain as complete a filling as possible of the pores of the separator with the electrolyte.*

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* See Bibliography, (73). † *Ibid.*, (74). ‡ *Ibid.*, (65), (77).
§ *Ibid.*, (70), (87), (88). || *Ibid.*, (81), (82), (94), (95). ¶ *Ibid.*, (86).

* See Bibliography, (70). † *Ibid.*, (75), (80). ‡ *Ibid.*, (77), (89).
§ *Ibid.*, (78). || *Ibid.*, (87), (88). ¶ *Ibid.*, (72), (73), (92), (93), (98).
** *Ibid.*, (66), (69).
†† *Ibid.*, (73), (79), (83), (84). ‡‡ *Ibid.*, (67), (74), (76), (96).

Subsequent treatment of the impregnated section depends upon the exact constitution of electrolyte that is used, and naturally, therefore, differs as between one manufacturer and another; as also do details of attachment of connecting wires to the lugs or tails of foil left projecting from each foil for terminal purposes, and the sealing of the sections into some form of outer container. This latter may be of metal or waxed cardboard or any other convenient material, in which the sealing of the condenser sections is provided by wrapping them in waxed or oiled paper and filling the container with wax or bitumen.

The drier types of electrolyte are particularly suited to the construction of condensers in cardboard and similar light mechanical enclosures, which are cheaper than the more robust aluminium or other metallic containers which are essential for the wet type and almost so for the semi-dry type of condenser as well.†

From the point of view of performance of the condenser it is necessary to seal the sections as perfectly as possible against ingress of moisture, just as in the case of any other condenser with more conventional dielectrics. The best condenser forms therefore comprise a metal outer container. One or more sections may be mounted into a common container, and no difficulties arise from connecting the negative foils together. Other connection groupings of the sections which may involve joining positive foils together, or positive and negative together in series connection, need special precautions to be taken to assure absolute separation of the electrolytes in the various sections.

(d) Ageing and Testing

When completed, the condensers—whether wet or dry—need an ageing process to repair any slight damage to the film that may have occurred in the course of handling the foil during manufacture. To this end they are usually assembled in banks or racks wherein they are joined across busbars to which an appropriate d.c. voltage is connected, and are maintained polarized in this manner for several hours, or until the leakage current passing through them falls to some predetermined value. Measurement of capacitance then follows before the completion of the article.

The capacitance measurement that is applied in the factory to these condensers when made on a mass-production scale needs to be the simplest possible. The impedance test most easily fulfils this requirement.* It consists in applying to the condenser a known fixed a.c. voltage (for example, about 20 volts) of known frequency (such, for example, as the 50-cycle controlled-frequency supply mains) and measuring the a.c. milliamperes that flow through the condenser. For a limited range the milliammeter can be calibrated in microfarads of condenser capacitance. When making this test it is necessary to apply to the condenser a d.c. polarizing voltage of some convenient value below its maximum peak rating, such that the sum of this voltage and the peak value of the applied a.c. testing voltage is below the rated maximum voltage of the condenser.† The circuit of the

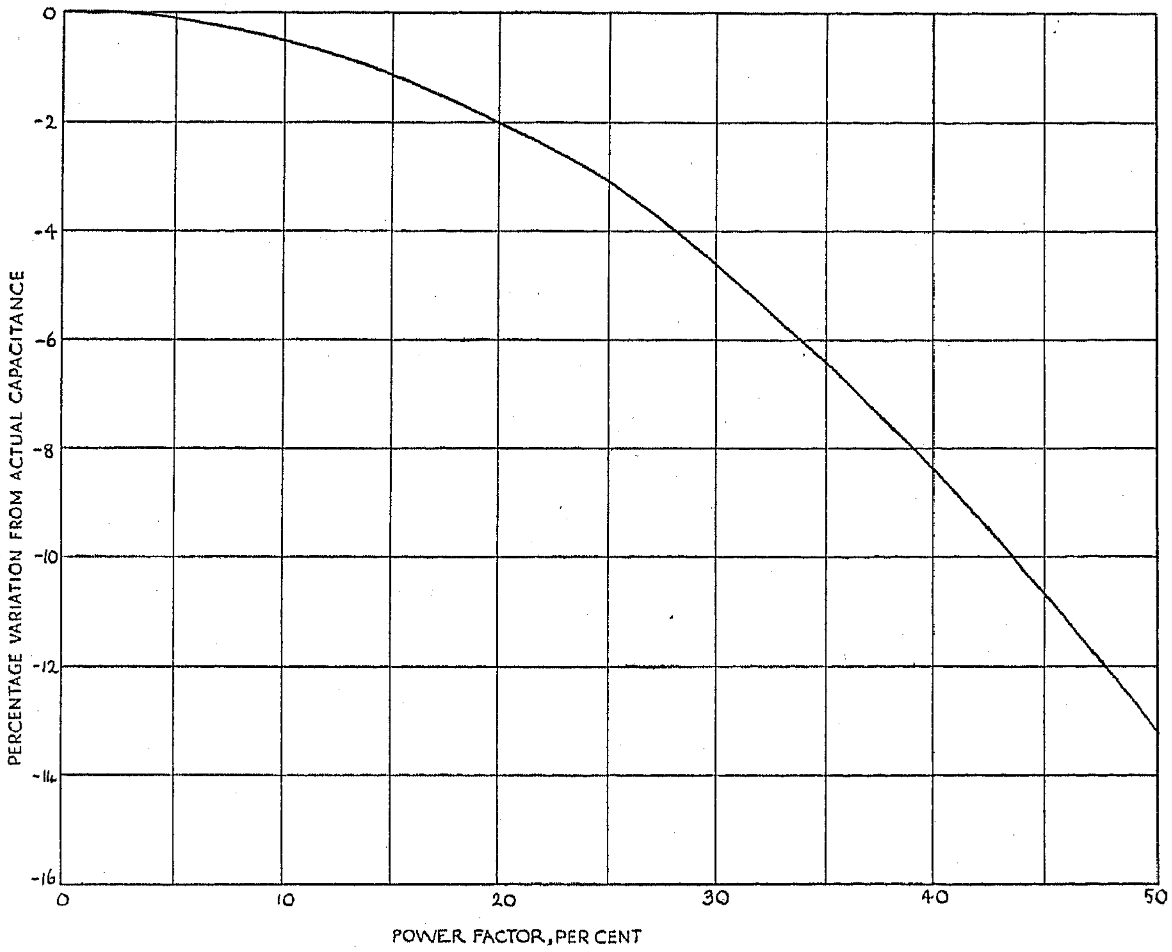

Fig. 7.—Effect of power factor of condenser upon its apparent capacitance as measured by the impedance method.

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* See Bibliography, (74).

† *Ibid.*, (56), (59), (61).

* See Bibliography, (49).

† In the Appendix the authors suggest a standard specification that can usefully be followed when making these tests.

arrangement comprises an a.c. ammeter and voltmeter of appropriate ranges only.

This impedance method of measuring capacitance is particularly useful for dry-type condensers wherein the power factor does not exceed 10 %, since the results of such measurements will agree with the true capacitance to within 0·5 % (Fig. 7).

As an alternative to the impedance test, an a.c. bridge method must be used. This enables the capacitance and loss-factors to be separated and these quantities to be determined individually. Such tests generally belong more to the laboratory than to the factory production department, owing to the greater time taken to make the measurements. Several forms of commercial testers for electrolytic condensers have, however, been marketed recently by instrument manufacturers. Some of these involve use of the bridge method. A convenient circuit arrangement is depicted in Fig. 8 which differs from a conventional a.c. bridge method only in the addition of the d.c. polarizing voltage for the test condenser, and of means for isolating the flow of current from this d.c. source through the remainder of the bridge circuits.*

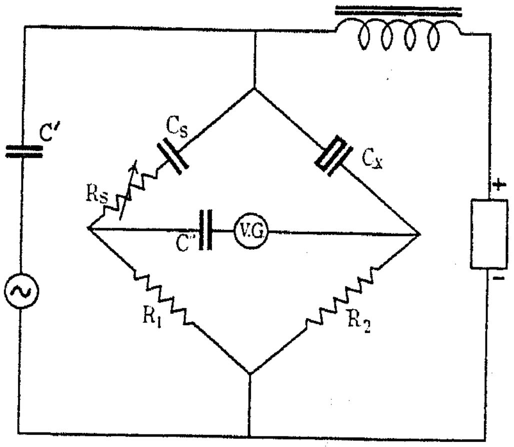

Fig. 8.—Bridge circuit for electrolytic-condenser measurement.

Throughout the manufacture of electrolytic condensers the greatest care is necessary to prevent contamination of any part of the condenser, and especially of the electrolyte. Many impurities are very harmful to the performance of the condensers; in particular, any materials which will liberate chlorine ions into the electrolyte† should be scrupulously avoided.

(5) CONDENSER CHARACTERISTICS

The properties of electrolytic condensers can be considered under four main headings, namely (*a*) capacitance, (*b*) leakage, (*c*) electrical losses, (*d*) service life.

It will be convenient to consider each of these in turn, and the manner in which it is dependent upon various other factors concerned in the construction of the condenser and in its mode of use. In various practical applications of the condensers not all these properties are of equal importance. As in the case of electrical condensers employing the more conventional dielectrics, it results therefrom that different condenser constructions are employed for different commercial applications. In such special constructions, one or other of these properties can be emphasized or greater dependence placed upon it, in order to fit the condenser as far as possible for its particular use.

The general scope of the various tests that are commonly made on these condensers by users of them differs at present very much as between one user and another, since no standardized scheme has yet been put forward. In the Appendix the authors set out a suggested specification for such tests, which is put forward as providing an adequate cover for all ordinary requirements of these condensers. The use of such a standardized testing procedure will be helpful to the manufacturers and also to all users of these condensers.

(a) Capacitance

Various methods of synthesizing or producing the dielectric film on the aluminium are employed, but its dielectric constant is not found to be altered thereby to any very great extent. The physical dimensions of the dielectric are therefore important factors which determine the condenser capacitance.

The area of the dielectric is fundamentally controlled by the surface area of the electrode, and by virtue of the intimate or atomic attachment between them any distortion of that surface (before formation) brings about—or at least should do so—a corresponding distortion of the dielectric. Appropriate distortions of the electrode surface can therefore increase its surface area, or rather its effective electrical surface area, without increasing its overall dimensions.*

For the type of condenser generally used in radio receivers, only one such electrode needs to be so treated. For the non-polarized type [see Sections (6)(*b*) and (6)(*c*)] both electrodes must be treated and must normally have similar effective areas.

While a maximum increase of about 10 times is possible, it is seldom that this full amount is used, and the higher-voltage condensers constructed in this way are more often given an increase of 3–6 times the normal.

Many different methods have been used to increase the surface area of the electrode. They are divisible into three categories—mechanical, chemical, and electrochemical. In the group of mechanical methods are included such treatments as sand-blasting, embossing of the surface by means of indented steel rollers,† or actual perforation by means of very minute holes.‡ In the chemical methods an etching treatment is sometimes adopted, using either strong alkaline or acid baths (or sometimes both in turn), either of which has the effect of roughening the surface. For the deepest form of etching, which gives the greatest capacitance increase, an acid treatment is usually most effective, and with electrodes of small thickness (that is to say, foil electrodes up to about 0·006 in. thick) actual perforation of the sheet may also take place as a result of this treatment.§ In the electrochemical treatments, solutions somewhat similar to those used in the chemical methods are often adopted, but the process is accelerated by means of electrolysis, the electrodes to be treated being made one pole in the electrolytic cell while an inert electrode is used for the other.‖ A deeper etching of the surface under more controllable conditions is often achieved by these treatments,

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See Bibliography, (50).

† *Ibid.*, (19), (20).

* See Bibliography, (65), (89).

† *Ibid.*, (90), (91).

‡ *Ibid.* (97).

Ibid., (97), (99).

‖ *Ibid.*, (100).

which also have the advantage that less chemically active electrolytic solutions can be employed. In fact, it is even possible to adopt this method with a relatively inert solution which will not normally attack the aluminium electrode and yet obtain a very deep etching treatment by the electrolytic etch. For example, a solution of common salt, used alone or sometimes with the addition of a little hydrochloric acid, is relatively harmless to the metal without the added electrolytic action. Even with such solutions, an area and capacitance increase as great as the largest mentioned above is achievable under quite stable manufacturing conditions.

The other main factor controlling the capacitance of the condenser is the thickness of the dielectric film. This is normally a direct function of the voltage under which the film is produced on the electrode by the pre-forming process. The physical thickness of the film is not, however, the controlling factor as regards its electrical capacitance, since quite frequently very thick films can be built up on to aluminium (as, for example, in some of the anodic treatments* used for the purposes of protecting aluminium articles against weathering) which behave electrically as only very thin films. Since, however, such anodic protection films are usually formed at low voltages, it is evident that the voltage applied during the forming treatment is the real controlling factor rather than the overall physical thickness.

It seems from this effect that all parts of the film are not equally effective in producing a dielectric barrier on the electrode. In some forming treatments it seems that the resistive layer is at the base of the physical layer and occupies only a very small fraction of its thickness. The most stable films, which are required for condensers for use in high-voltage circuits, are generally the most coherent and solid and have much smaller overall physical thickness than many of the lower-voltage films. The electrolyte used in forming the dielectric film, as well as its temperature and the time occupied by the treatment, exerts also some influence on its effective thickness and capacitance.

(b) Leakage

This term relates to the current which flows through the condenser under its applied d.c. polarizing voltage. It is, however, not nearly such a constant or definite quantity as the capacitance, and it is dependent upon a larger number of factors included in the conditions of measurement. In addition, it is a function of the type of film pre-formation that has been employed in the manufacture of the condenser and of the electrolyte used in the condenser. In fact, a study of the leakage current as a function of the various factors that affect it gives a valuable insight into the constitution and general service performance of the condenser. This aspect is dealt with in Sub-section (*e*) below.

(c) Electrical Losses

The losses—or power factor—arise from the flow of the capacitance-current through the series resistance of the electrolyte, from true dielectric losses in the film itself, and also in part from the d.c. leakage. The last component is generally a small one only. Usually it is not necessary to envisage any separation of the first two parts, but merely to group them all together under the term " power factor." A method of measuring this quantity is discussed in Section (4)(*d*). Like the leakage, however, the losses are functions of temperature, voltage, and other conditions of measurement, as well as of the construction of the condenser; so that it is useful to consider the manner of this variation at the same time as that of the leakage current.

(d) Service Life

The useful effective or service life of a condenser depends solely upon the maintenance of a reasonable proportion of its initial properties—chiefly capacitance and leakage. Generally, the tendency is for the capacitance to fall and for the leakage and losses to rise after the lapse of considerable time in use. The end of the useful life is determined by the capacitance becoming too small to give effective operation, or by the d.c. leakage becoming excessive, or by the power factor becoming so great that overheating occurs due to the ripple current flowing through the condenser, or by its filtering action becoming spoiled if the condenser is used in a by-pass or smoothing circuit. The service life of a condenser is therefore controlled in the same way and by the same factors as affect these three fundamental condenser properties, which are considered more fully in Sub-section (*e*).

There is, however, another aspect of condenser " life " which deserves mention—its " shelf life." Usually some deterioration takes place in an electrolytic condenser when it is standing, even if it is not in use at all. This may be regarded as somewhat analogous to the deterioration which takes place in a dry battery on the shelf, since this also is an electrolytic device. The aim of modern manufacturing methods is to prolong the shelf life as much as possible, by increasing the stability of the dielectric film so that all changes in its properties tend to become minimized (see Fig. 14).

(e) Dependence of Condenser Properties upon Conditions of Measurement and Use

The properties of electrolytic condensers are none of them invariable quantities, independent of the conditions of use and of the conditions of measurement of those quantities. The capacitance, the d.c. leakage, the a.c. losses, and the useful life, are all functions of the following four factors: (i) Magnitude of applied d.c. voltage. (ii) Time of application of voltage. (iii) Working temperature. (iv) Magnitude and frequency of a.c. voltage.

The form of these variations can best be expressed by means of curves illustrating typical measurements.

(i) General: Condenser " characteristics."

The variation of capacitance with the magnitude or with the period of application of the applied d.c. voltage is usually not serious with the aluminium electrolytic condenser (Fig. 9).* The variation of capacitance with temperature for most forms of such condenser is also not large over the normal working range of temperatures, but at temperatures below freezing point the changes become much greater, and some forms of electrolyte and condenser construction show much larger changes than do others at low temperatures. Generally, electrolytes containing ethylene glycol as the base, and particularly those containing this material in considerable quantities, show the best maintenance of capacitance at the lower temperatures. The change of capacitance with time of application of the voltage to the condenser becomes, in fact, the service life of the condenser, the termination of such useful life being most generally determined by the loss of capacitance becoming greater than is permissible for the circuit in which the condenser is being used.

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* See Bibliography, (71), (75).

* These curves also show that the effective capacitance is in addition a function of the a.c. voltage applied to the condenser.

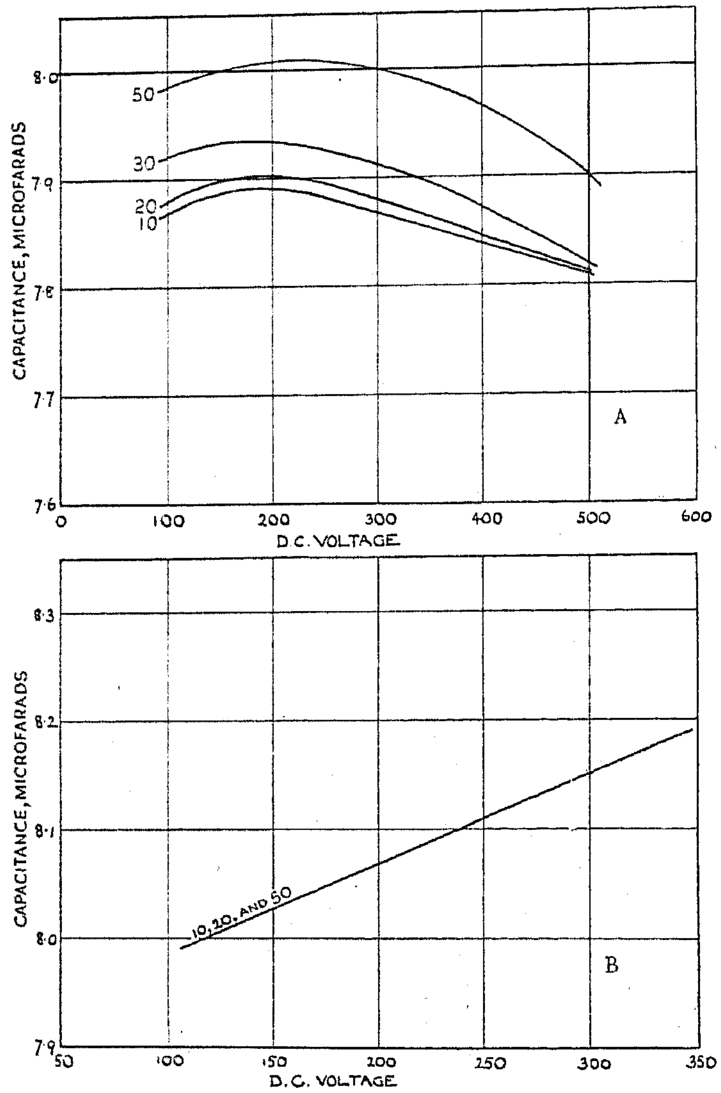


Fig. 9.—Dependence of apparent capacitance of electrolytic condensers upon the magnitudes of the d.c. polarizing voltage and of the superimposed a.c. ripple voltage.

A. Wet-type condenser.
B. Dry-type condenser.

Both sets of curves relate to 8-μF 500-volt condensers. Numbers marked against curves indicate a.c. ripple voltages.

The variation of the d.c. leakage with the first three determining conditions provides the three most useful characteristics of electrolytic condensers: the first one, namely the variation with applied d.c. voltage, is usually known as the voltage characteristic (Fig. 10); the second, namely the variation with time, being known as the re-forming characteristic (Fig. 11); and the third, the variation with temperature, being the thermal characteristic (Fig. 12). These three are fundamental characteristics of all electrolytic condensers.

The changes of electrical losses (that is, a.c. losses) with the same three factors are generally more analogous to the changes of capacitance with these factors than they are to the changes of d.c. leakage (Fig. 13).

(ii) Voltage characteristic.

The voltage characteristic is controlled mostly by the voltage at which the dielectric coating has been formed on the anode of the condenser, and the point at which the leakage current begins to rise rapidly with increasing d.c. applied voltage bears usually a direct relationship to that forming voltage (Fig. 10). Certain applications of electrolytic condensers which are often referred to as " regulating condensers " require a construction in which the rise of leakage with voltage follows a very steep curve [see Section (6)(*d*)].

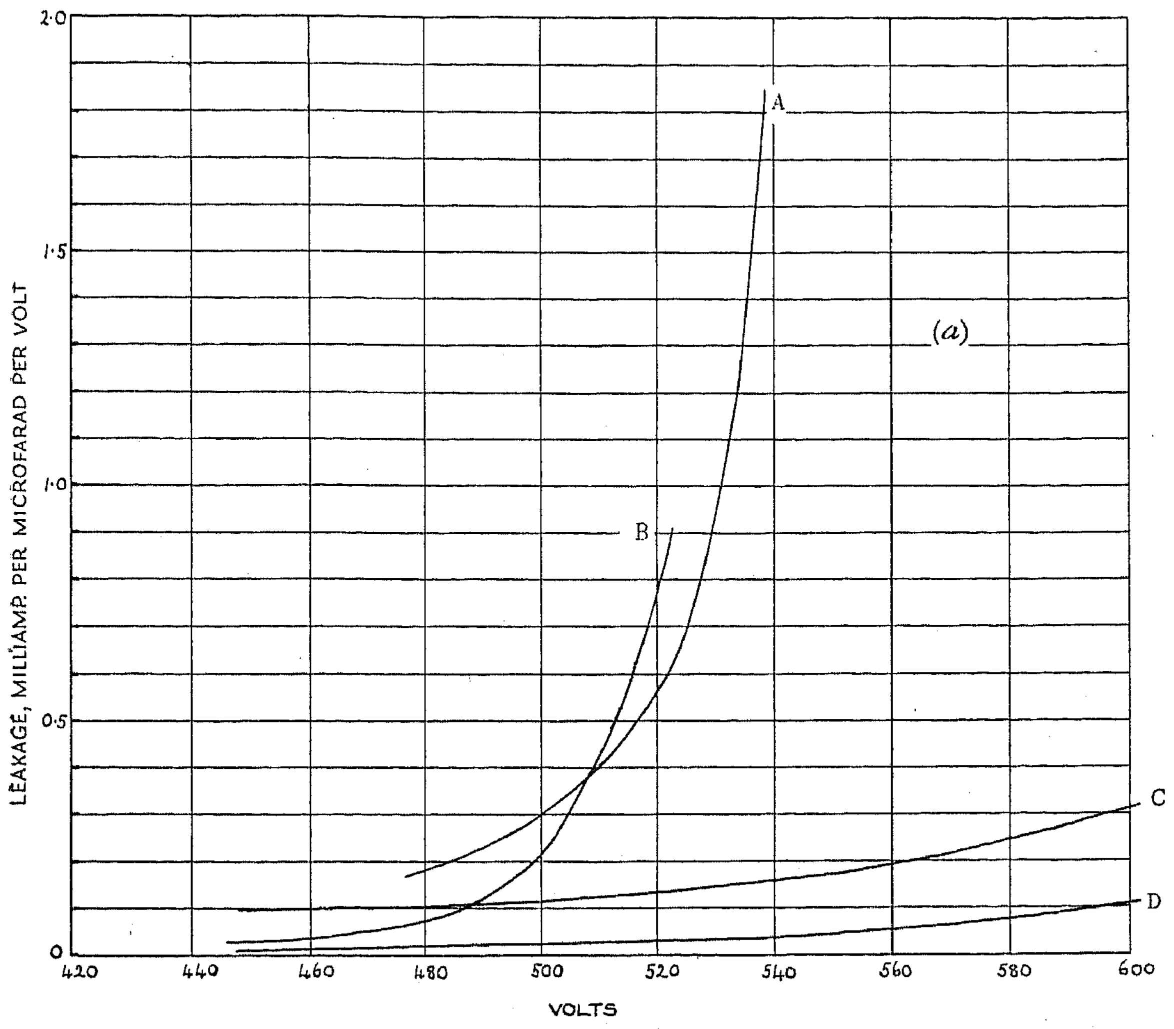
The presence of this bend in the characteristic may generally be taken as indicative of the maximum working voltage which it is safe to apply to the condenser for anything more than the shortest of periods. This is the case both because the excessive voltage might puncture the dielectric, and also because the large leakage current thereby produced would cause overheating of the condenser if its application were prolonged.

The shape of this voltage characteristic forms, therefore, some guide as to the construction of the condenser, the manner in which it will behave under given operating conditions, and the type of use to which it should be put. It is a very useful guide both to the manufacturer of the condensers and to the users when making inspection tests.

(iii) Re-forming characteristic: film stability.

The variation of leakage current with time of application of applied voltage, which is usually known as the re-forming characteristic (Fig. 11), constitutes one of the most important characteristics of an electrolytic condenser. It is a direct measure of the stability of the dielectric film, since any deterioration of the film in the working electrolyte of the condenser which may take place when the condenser is not in use—or is " idling "—will need to be repaired by the re-forming action when voltage is again applied to the condenser. Any excessive repair will imply passage of an excessively large leakage current during the repairing period. With a stable film the current drawn by the condenser, when voltage is first applied to it, will decrease very rapidly to the ultimate limiting leakage current. The most stable and the most useful condenser is generally, therefore, one in which the leakage current is not only normally low but is restored to this low value very rapidly even after a prolonged idling period. There may be exceptions to this general rule in the case of certain applications of condensers, but such need always to be treated as special cases.

Fig. 14 shows re-forming characteristics taken on 500-V dry condensers after various periods of idling up to 12 months. The uniformity of these emphasizes film stability. Fig. 15 gives corresponding curves for 25-volt dry condensers, and with these a somewhat lower degree of stability is to be noted, particularly after 12 months of idling. The fact that when these tests are repeated at 75 % of the rated voltage of the condenser no such apparent deterioration is observed, shows that there has been some disintegration of the film in the electrolyte. This phenomenon is observed to a much greater extent in wet electrolytic condensers, so much so that the plotting



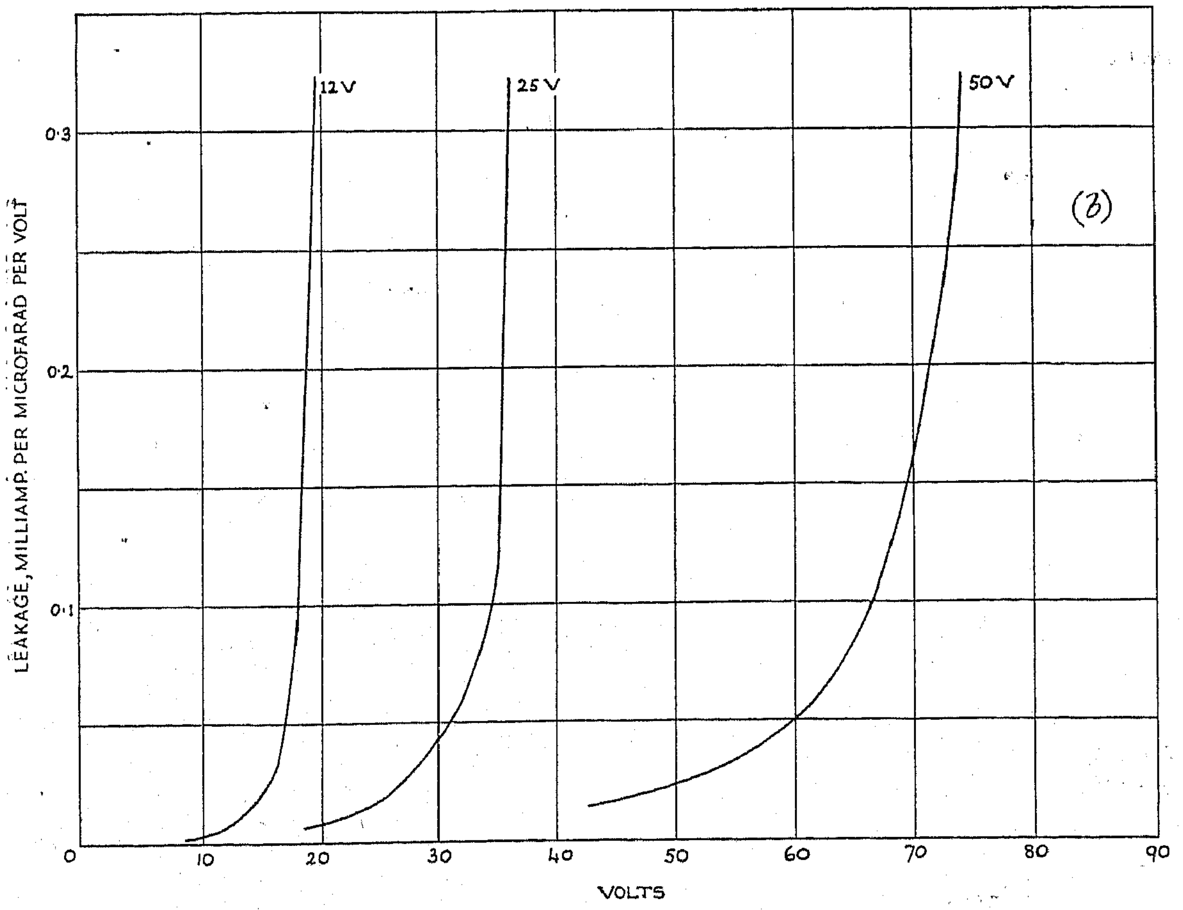


Fig. 10.—Voltage characteristics of electrolytic condensers.

(*a*) High-voltage (500 volt) condensers. Curves A and B, wet types; Curve C, semi-dry type; Curve D, dry type.
(*b*) Low-voltage condensers.

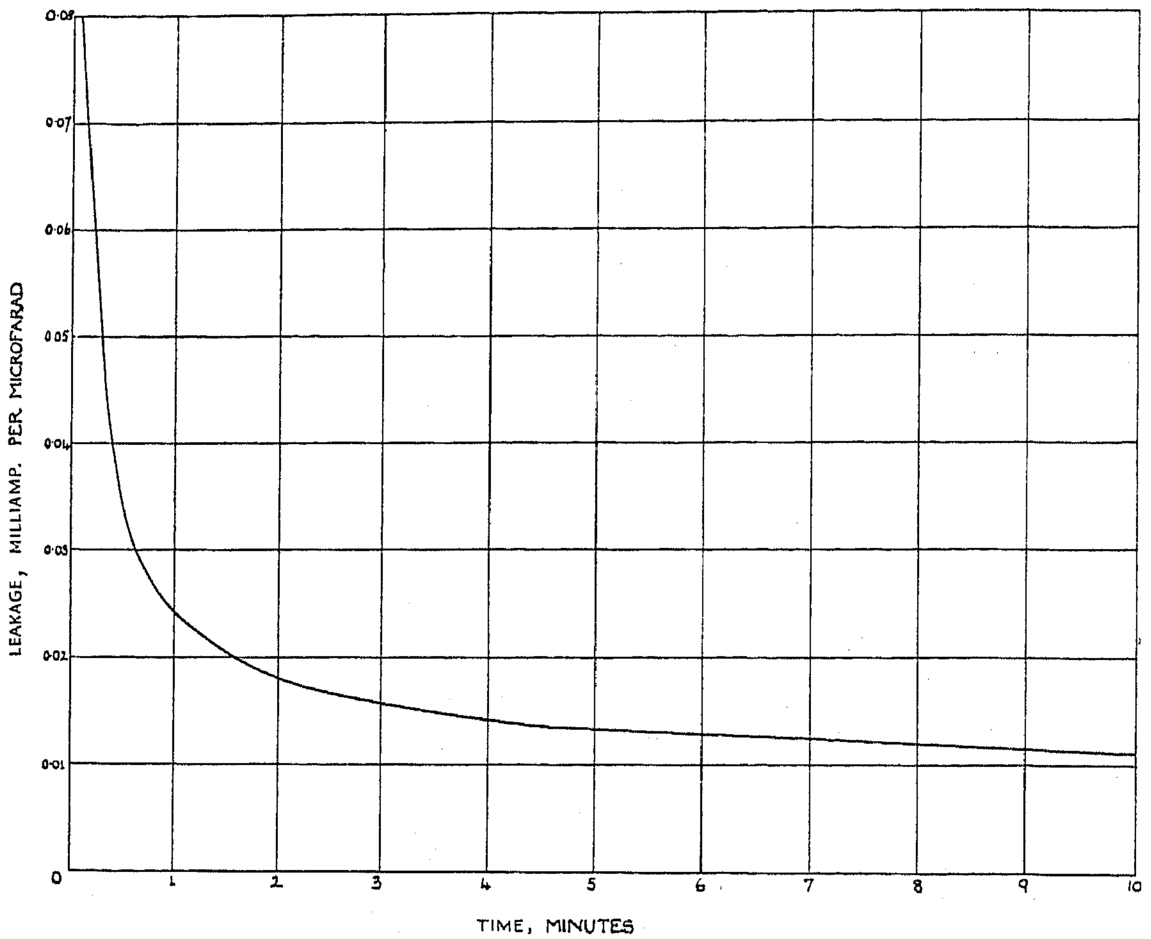


Fig. 11.—Re-forming characteristic of dry-type condenser (8 μF, 500 V). Test taken after 100 hours at rated voltage, followed by 100 hours' idling.

of re-forming characteristics on the lines of Figs. 14 and 15 is often impracticable.

The film stability as judged in this way forms quite a good measure of the ability of the condenser to give a long shelf life. This is quite apart from the operating life of the condenser, which, in addition to the factors indicated above, is controlled also by the amount of electrolyte in the condenser. Thus constructions having a considerable bulk of separator between the electrodes to contain the electrolyte can generally give a longer service life before the electrolyte is exhausted.

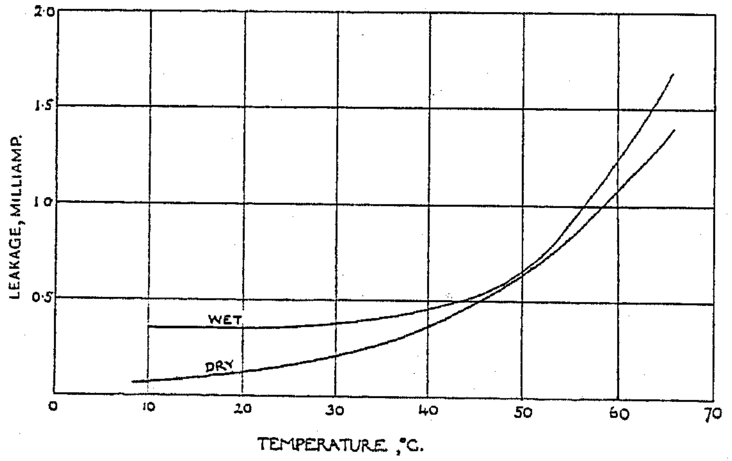


Fig. 12.—Thermal characteristics of wet and dry types of condensers.

(iv) Thermal characteristic.

The utility of the thermal characteristics for judging the qualities of a given condenser is mainly limited to those applications in which the condenser may be sub-

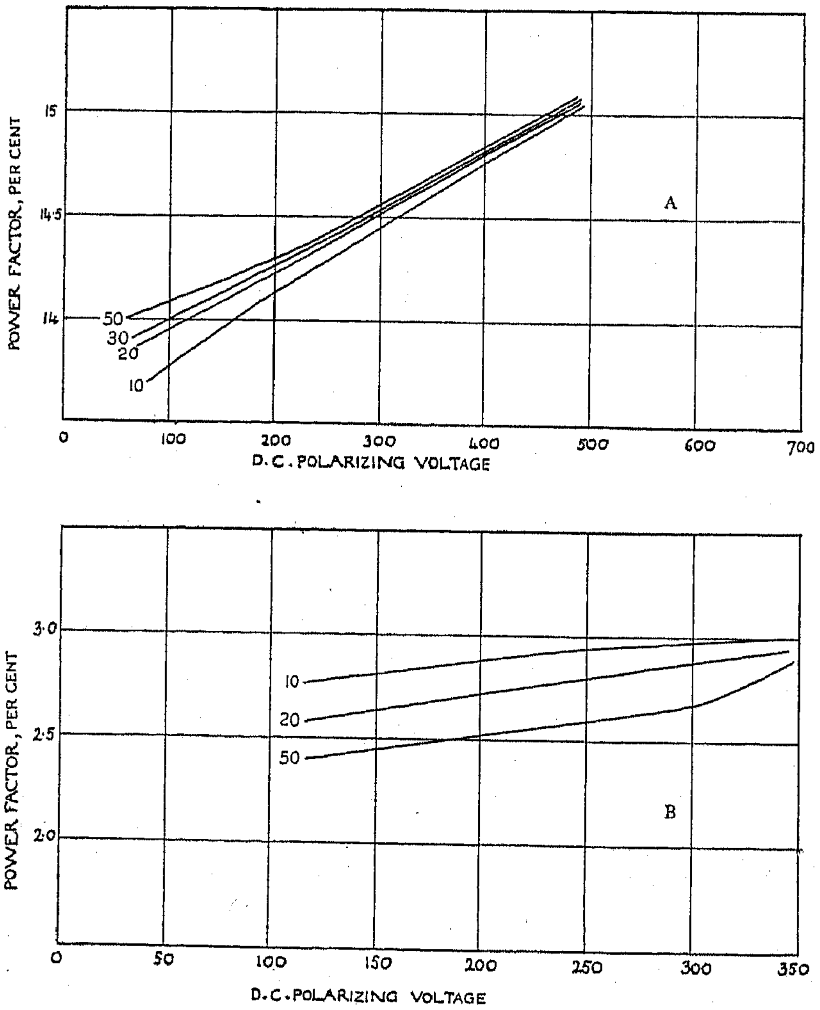


Fig. 13.—Dependence of power factor upon the polarizing voltage and superimposed a.c. ripple voltage.

A. Wet-type condensers.
B. Dry-type condensers.

These two sets of curves correspond with A and B in Fig. 9.

jected to extremes of temperature. For normal uses the thermal characteristic is not of very great importance unless the rate of rise of the leakage curve with temperature is very sharp. Should this be the case, the condition may arise when an increase in temperature of the condenser due to its being mounted in some apparatus which has become warm in service, may give rise to so much increase in the leakage current that still further heating may take place in the condenser owing to this rise. Such a condition may lead to a progressive rise in temperature until breakdown of the condenser occurs. With all normal types of modern electrolytic condensers such an occurrence is, however, extremely unlikely (Fig. 12). The thermal characteristic of the condenser as regards its a.c. losses may be a much more serious one from this point of view, since, if the condenser is called upon to pass any considerable amount of ripple current when it is used as a reservoir or smoothing condenser in an a.c. rectifier system, the loss resulting therefrom (which is translated into heat) is generally very much greater than the energy loss in the condenser due to the d.c. leakage. When this is the case, if the power factor of the condenser increases

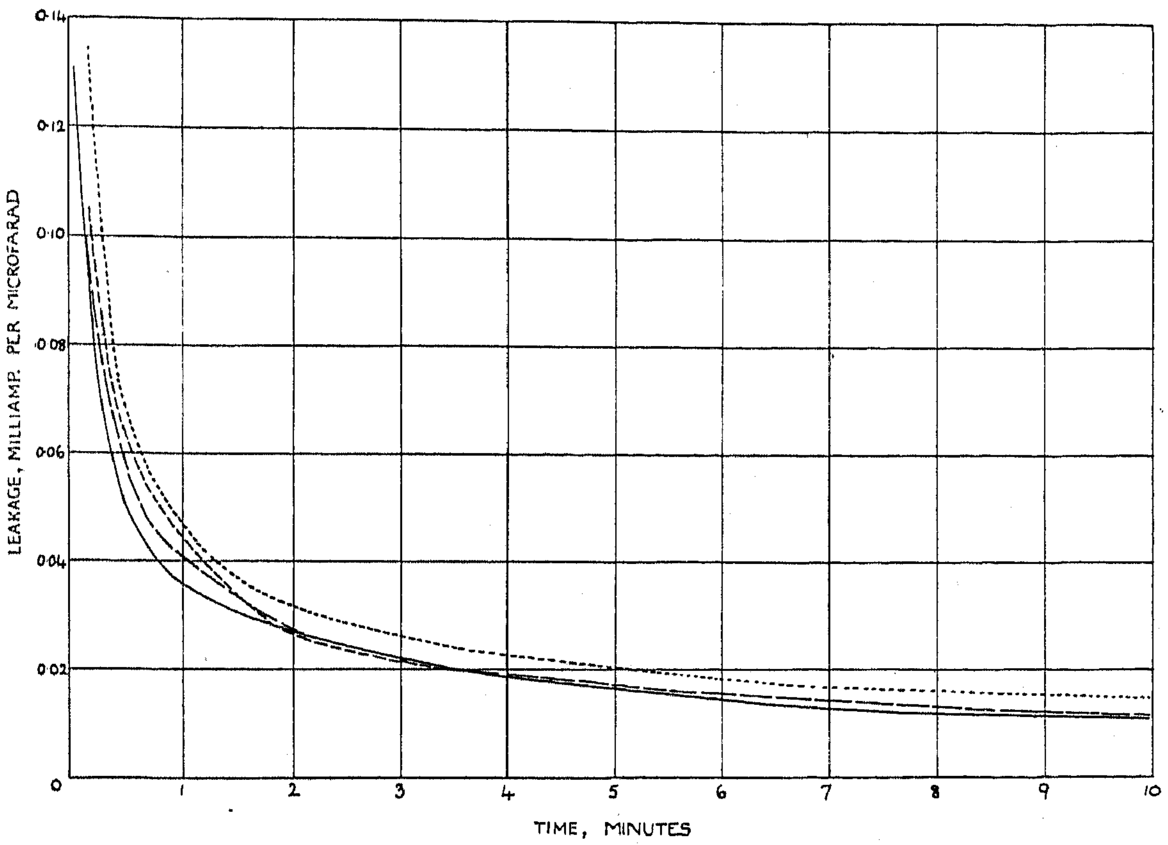


Fig. 14.—Re-forming characteristics of high-voltage dry-type condenser (500 V) after various periods of shelf idling.

———— After 3 months' idling.
— — — After 6 months' idling.
------- After 9 months' idling.
.... After 12 months' idling.

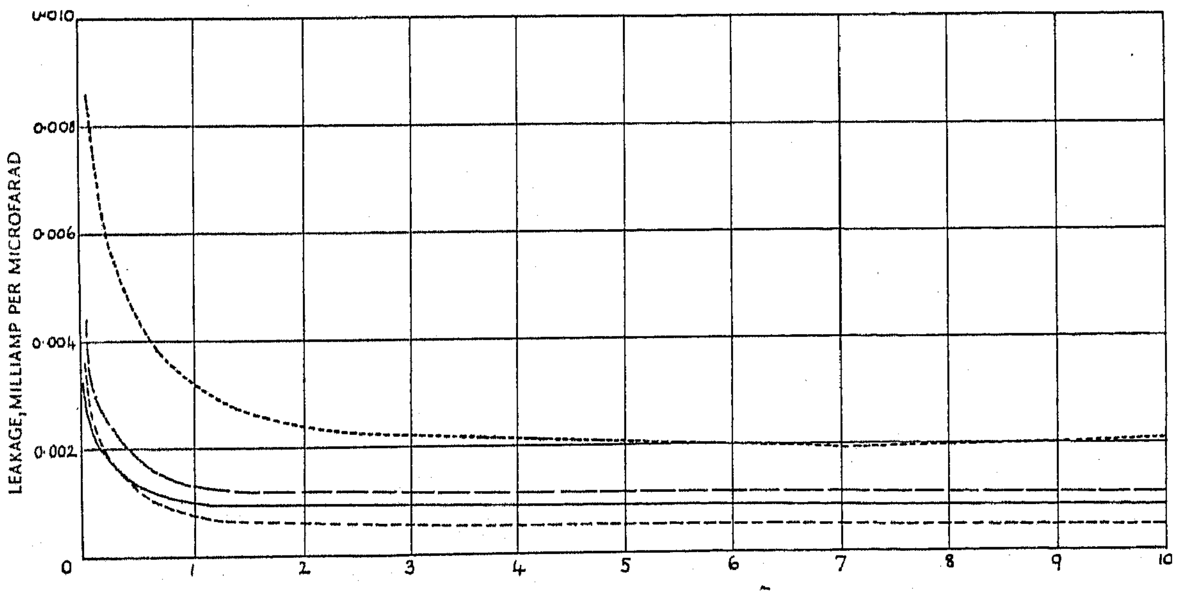


Fig. 15.—Re-forming characteristics of low-voltage dry-type condenser (25 V) after various periods of shelf idling.

———— After 3 months' idling.
— — — After 6 months' idling.
------- After 9 months' idling.
.... After 12 months' idling.

very much with rise of temperature, the losses in the condenser due to the ripple current may increase the temperature so rapidly that an unstable and dangerous condition is very quickly reached. It is therefore of advantage if the power-factor characteristic falls with increasing temperature, and with many of the modern dry electrolytes this feature is attained at least up to a temperature of 50°–60° C. Above this point the characteristic may bend round and rise with increasing temperature, so that the safe working limit of temperature for such condensers will not usually much exceed this point of minimum power-factor value, except in such cases as when the condenser is passing so little ripple current in normal use that the heating produced thereby is negligible (Fig. 16).

(v) Time characteristic: life.

The quality of an electrolytic condenser for any given application cannot be judged solely from any given simple measurements, such as of capacitance or leakage current. To obtain a complete picture of the probable behaviour of a condenser, it is usually necessary to determine all the characteristics which have been detailed above. Generally speaking, condensers which have etched or similar treated anodes will be broadly similar in performance and characteristics to those made without such treatment, but the reduced bulk generally implies also a reduced capacity for dissipating the heat due to the passage of ripple currents, so that the application of such condensers in circuits passing such currents needs to be watched with more caution than the application of condensers of the normal type. Even in situations where the ripple current is negligible, it has to be remembered that a reduced bulk means a smaller quantity of electrolyte and therefore some risk of a shorter effective life.

In Fig. 17 are plotted the capacitance readings taken on a wet type and two different types of dry electrolytic condensers at various times up to nearly 12 000 hours of continuous life at 50° C., which represents the highest temperature which should normally be reached inside a radio receiver. These readings have been plotted as a percentage of the nominal rated capacitance of the condenser, since in judging its effective life the user is generally concerned primarily with the capacitance not falling below, say, 90 % of the rated value he has chosen. These curves are typical as showing the larger changes of capacitance often observed with dry-type condensers, although in the case of a wet condenser should any substantial wastage of electrolyte occur (as by repeated sparking or by actual leakage) a sudden and large fall of capacitance may be observed.

It is very difficult to generalize on the question of the probable life of an electrolytic condenser. With suitable use it should amount to at least 2 years, and is often very much longer. There are very many fortuitous circumstances and possible faults which may lead to a reduction of life. It is, however, certain that the useful life will be over once the electrolyte has been used up. Generally speaking, therefore, the probable life is indicated by the leakage of the condenser. Thus, a high leakage current due either to a high temperature or to operation too near the breakdown voltage will give a shorter life than normal operation.

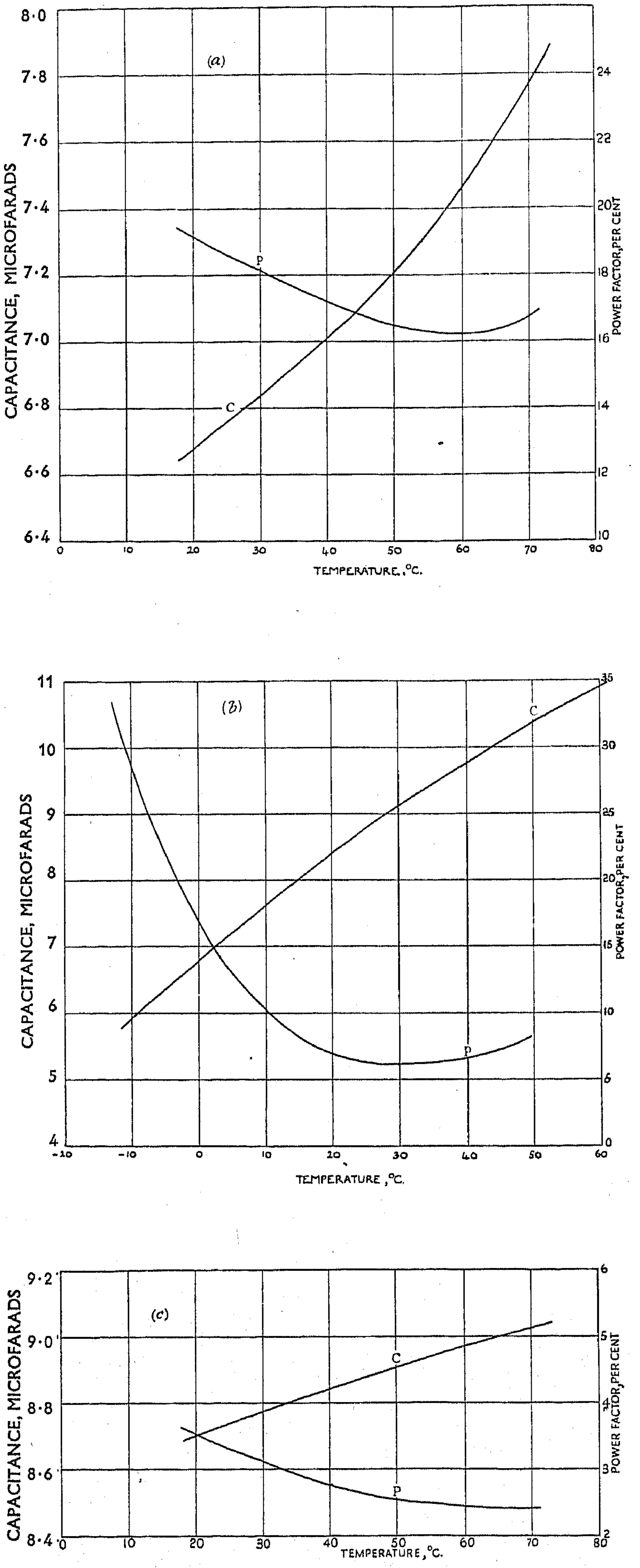


Fig. 16.—Thermal characteristics of capacitance and power factor of condensers.

(*a*) Wet type. (*b*) Semi-dry type. (*c*) Dry type.

The action in the electrolyte for a " dry " electrolytic condenser is somewhat obscure, and not much is known about the deterioration of the electrolyte due to the passage of the leakage current. Claims have been made that the conduction in a " bone dry " electrolytic condenser is electronic. If this were true there would be no obvious way of accounting for the falling-off in capacitance of such a condenser. It is probably more justifiable to assume that in the " dry " types there is an appreciable amount of reverse action or recombination, and therefore the electrolyte is not used up as fast as Faraday's laws would lead us to expect.

Applying Faraday's laws of electrolysis to the aqueous constituents of the electrolyte, and assuming normal electrolytic conduction, a life of some 10 years of continuous use may be expected. This would be true if the electrolyte were the only controlling factor. Even with this reservation it must be pointed out that where an aqueous electrolyte is used under conditions of sparking, such as when a wet condenser is used as a voltage limiter in apparatus using rectified alternating current, the volume of gas evolved may be as much as 10 times greater than that given by Faraday's law.[*] In such circumstances a comparatively rapid loss of electrolyte sometimes occurs, with consequent equally rapid failure of the condenser.

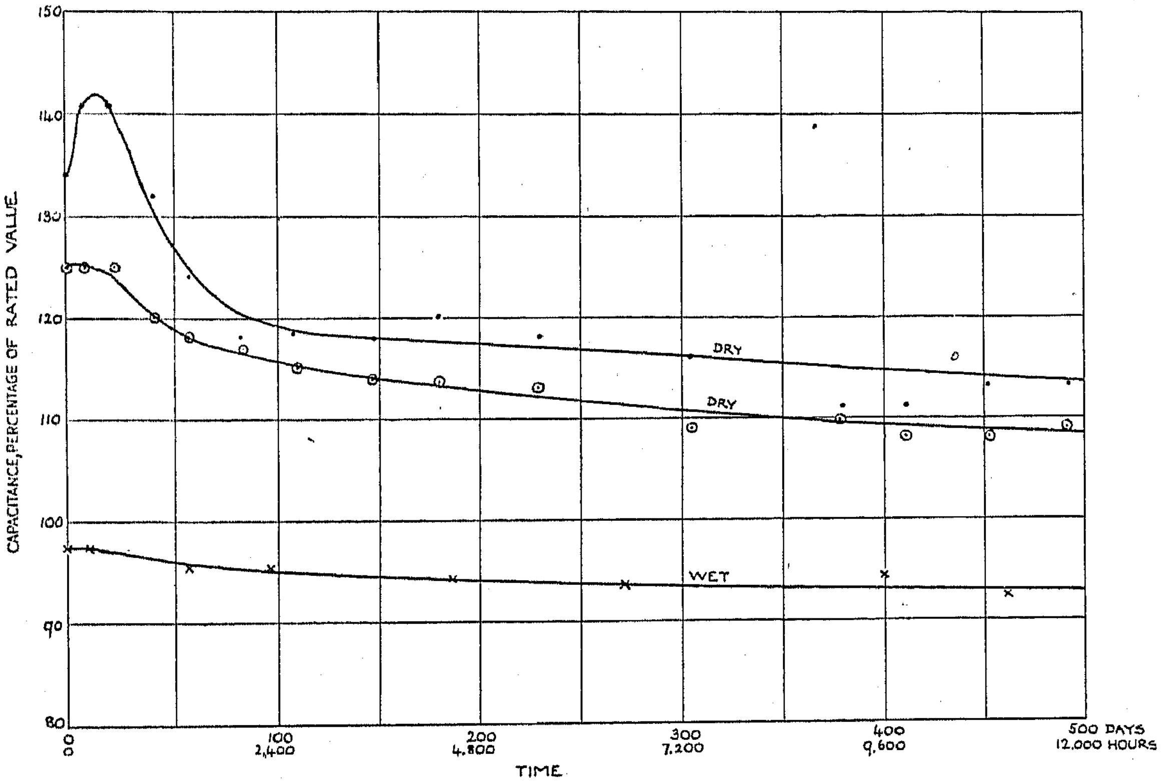


Fig. 17.—Time characteristics, or " life " curves, of dry and wet types at 50° C. and 500 volts d.c.

—●——●— Dry type, 18 μF, 500 V.
—⊙——⊙— Dry type, 18 μF, 500 V.
—×——×— Wet type, 16 μF, 500 V.

Apart from the deterioration of the electrolyte, there are two other factors that may contribute to the loss of capacitance of the aluminium electrolytic condenser.

The first is clogging-up of the porous positive film, either by a deposit of crystals or precipitates from the electrolyte, or by aluminium salts in the colloidal state. In either case a new positive plate will be found to restore the capacitance. If the deposit is one of crystals from the electrolyte, the capacitance can be restored by merely washing out the deposit from the surface of the positive plate.

The second cause of deterioration is cathodic oxidation in condensers carrying a.c. ripple. Zimmerman[*] showed that the effect of alternating current superposed on direct current is to cause a back-and-forth movement of the electric charges. When the positive charge moves to the cathode, i.e. when the a.c. depresses the d.c. voltage, a positive film tends to form on the cathode. Siegmund[†] and Godsey[‡] have referred to this phenomenon. The former makes two suggestions for minimizing the formation of this oxide coating on the cathode, namely (*a*) Use of impure aluminium for the cathode (less than 99 % Al). (*b*) Restricting the alternating current to 1 mA per cm^2 of plate area, even with the impure aluminium cathode.

In some " wet " condensers copper cans have been used as cathodes, but the copper usually contaminates the electrolyte and causes deterioration. A more modern idea is the use of aluminium cans as cathodes but with a coating of chromium plating inside. This, however, possesses the disadvantage that severe a.c. ripple overload causes the coating to come off and thus spoils the condenser. Another method is to roughen the cathode—either mechanically or chemically—so as to increase its effective area and so reduce the loss of capacitance arising from any film formation on the increased area.

(6) PRACTICAL APPLICATIONS

(a) In Rectified A.C. Circuits

It has been mentioned that the present-day electrolytic condenser owes its development to radio receivers and amplifiers, which call for large-capacitance condensers with the minimum of physical dimensions. These condensers are used for smoothing rectified alternating current, and may be divided into two principal categories:—

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[*] See Bibliography, (21), (22).

[*] See Bibliography, (23).

[†] *Ibid.*, (24).

[‡] *Ibid.*, (25).

Low-voltage types.—Condensers of capacitances generally between 6 and 50 μF, suitable for operation at voltages of 6 to 100 V. These are usually used for by-passing undesired low frequencies in grid-bias circuits.

High-voltage types.—Condensers with capacitances of 3 to 24 μF, for operation at voltages of 200 to 550 V. These are principally required for smoothing rectified a.c. supplies to the anode circuits of the valves.

While electrolytic condensers in normal use are required for by-passing audio frequencies only, it is of interest to designers sometimes to know the behaviour of these condensers at higher frequencies. Fig. 18 shows the equivalent series resistance of a 6-μF 500-V condenser of the dry type at various frequencies up to 1 Mc./sec., while Figs. 19 and 20 show the impedance and capacitance of 8-μF wet and dry types in the audio-frequency range. The effective capacitance at radio frequencies is of no practical importance, since the impedance may be taken to be equal to the effective series resistance.

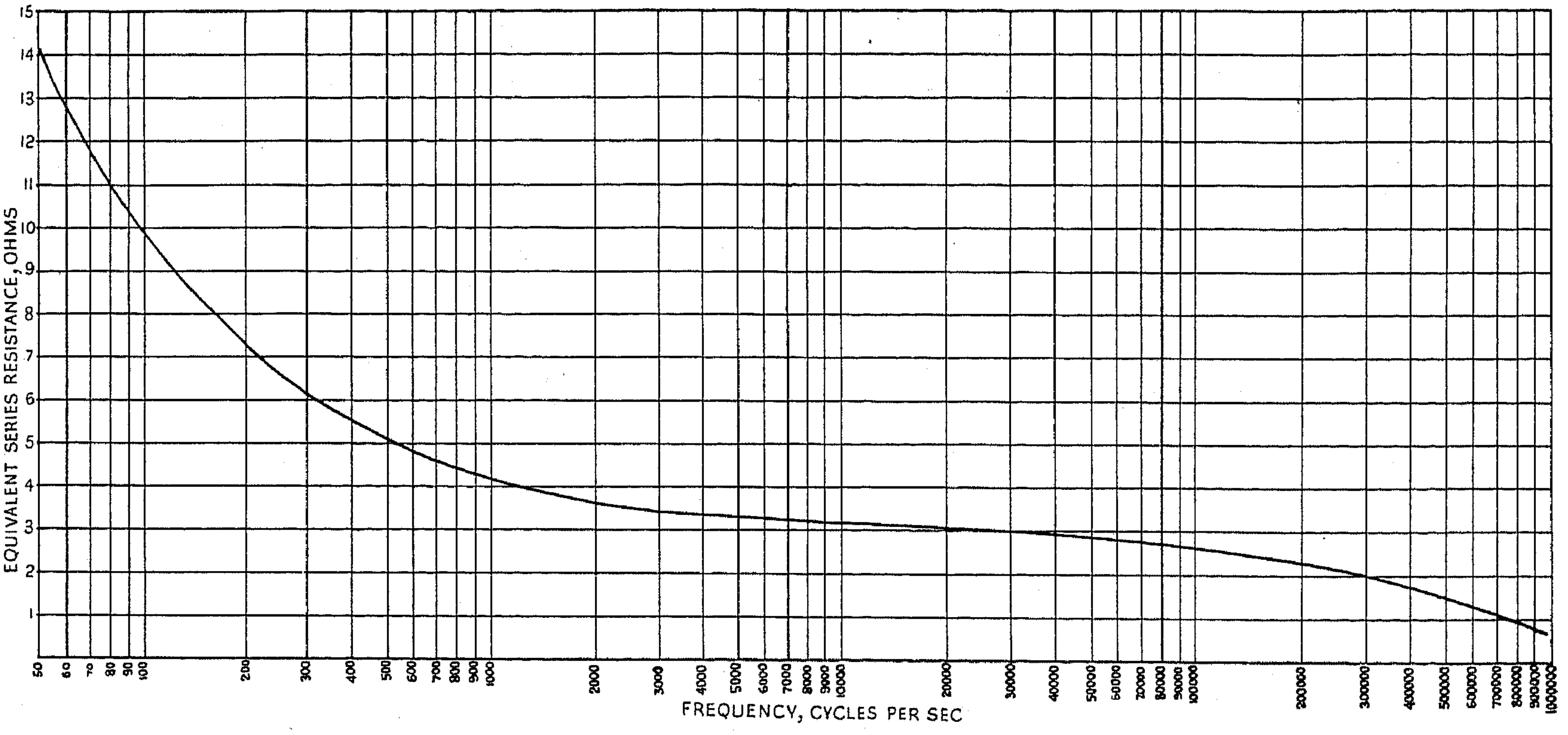

Fig. 18.—Dependence upon frequency of the equivalent series resistance of a dry-type condenser (6 μF, 500 V).

It is difficult to lay down any hard-and-fast rules for the choice of a particular type of condenser, but the following points may be taken as a general guide:—

(i) If a low power factor, as such, is desirable, the dry or semi-dry types will give a lower power factor than the wet type.

(ii) If a wide range of working temperatures has to be catered for, the wet type will, in general, give lower stability of operation and characteristics. This is particularly true at extremes of temperature.

(iii) If the condenser is required to function as a voltage limiter by drawing a large leakage current while the rest of the load is inoperative, as with slow-heating valves, a wet electrolytic condenser should be chosen on the grounds of reliability and length of service.

(iv) A wet electrolytic condenser must be mounted vertically with the vent above the level of the electrolyte. A dry electrolytic condenser, on the other hand, may be fixed in any position and must be used where unusual orientations of the apparatus are contemplated.

(v) If the apparatus incorporating electrolytic condensers has to lie idle for long periods, the dry type is preferable. This is in some measure due to the fact that the dry ones can be very effectively sealed, and in general have greater film stability.

In the applications mentioned in this section it has been assumed that there is a steady unidirectional voltage applied with an alternating or " ripple " voltage superimposed which it is the purpose of the condenser to shunt or " smooth out." When using the polarized condenser with a formed anode and a plain cathode it is essential to observe the following precautions:—

First, the positive side of the d.c. supply must be connected to the anode or positive of the condenser. A reversal will cause the condenser to act substantially as a short-circuit.

Secondly, the sum of the steady voltage and the peak value of the alternating voltage must not exceed the rated working voltage of the condenser; in general, this total should normally be about 85 % of the condenser rated voltage. This figure covers mains-voltage variations and other transients. An excess of voltage may cause increase of leakage current or even scintillation, leading to overheating and rapid deterioration of the film.

Thirdly, the peak value of the ripple must not exceed the steady voltage, i.e. there must be no " negative " peaks. Such transient reversals of polarity cause the introduction of harmonics due to partial rectification and also lead to a rapid reduction of capacitance owing to the formation of a film on the cathode, the effective capacitance then being that due to the two capacitances of the anode and cathode films in series.

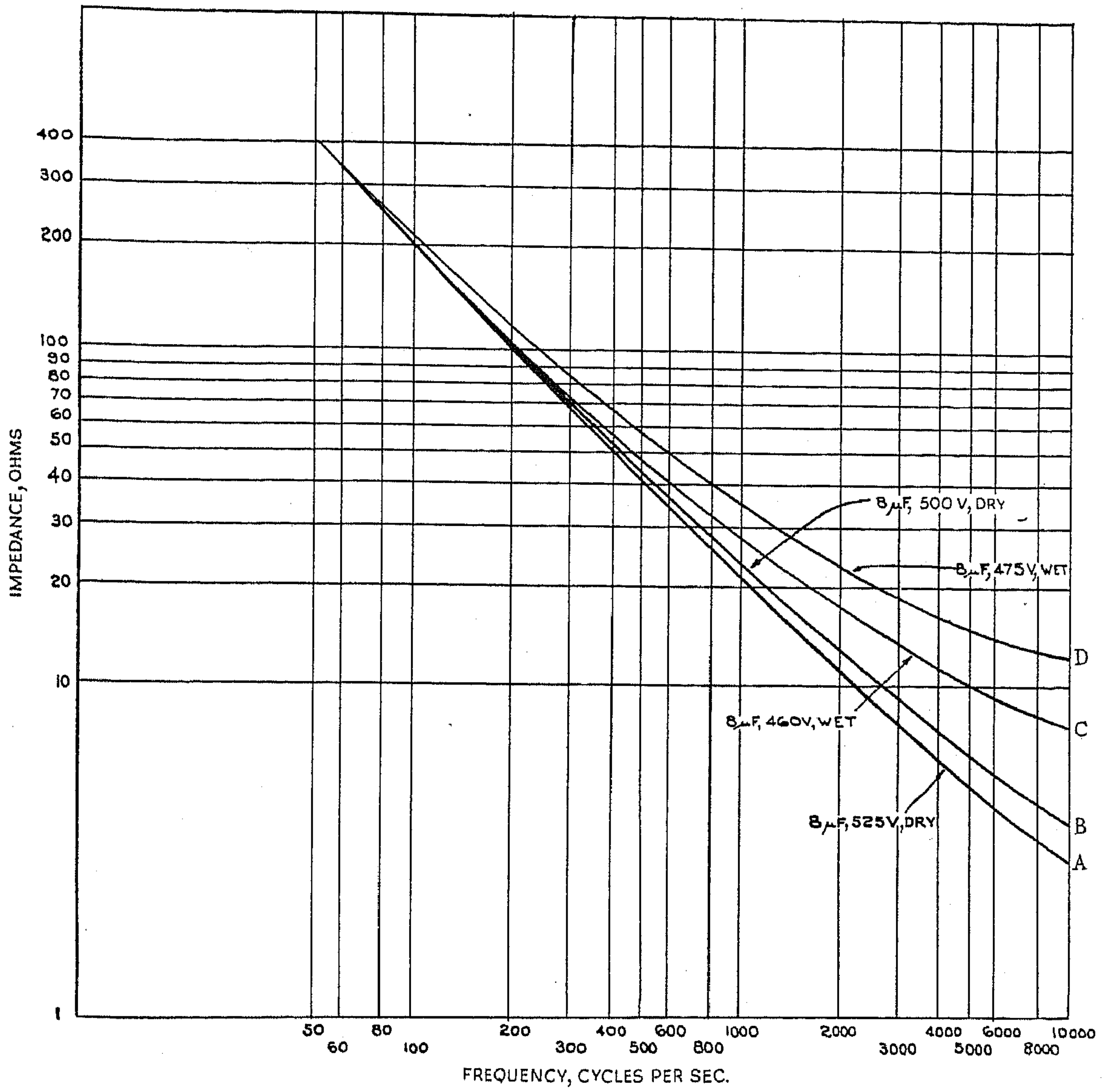

Fig. 19.—Impedance/frequency relations of wet and dry types of condensers.

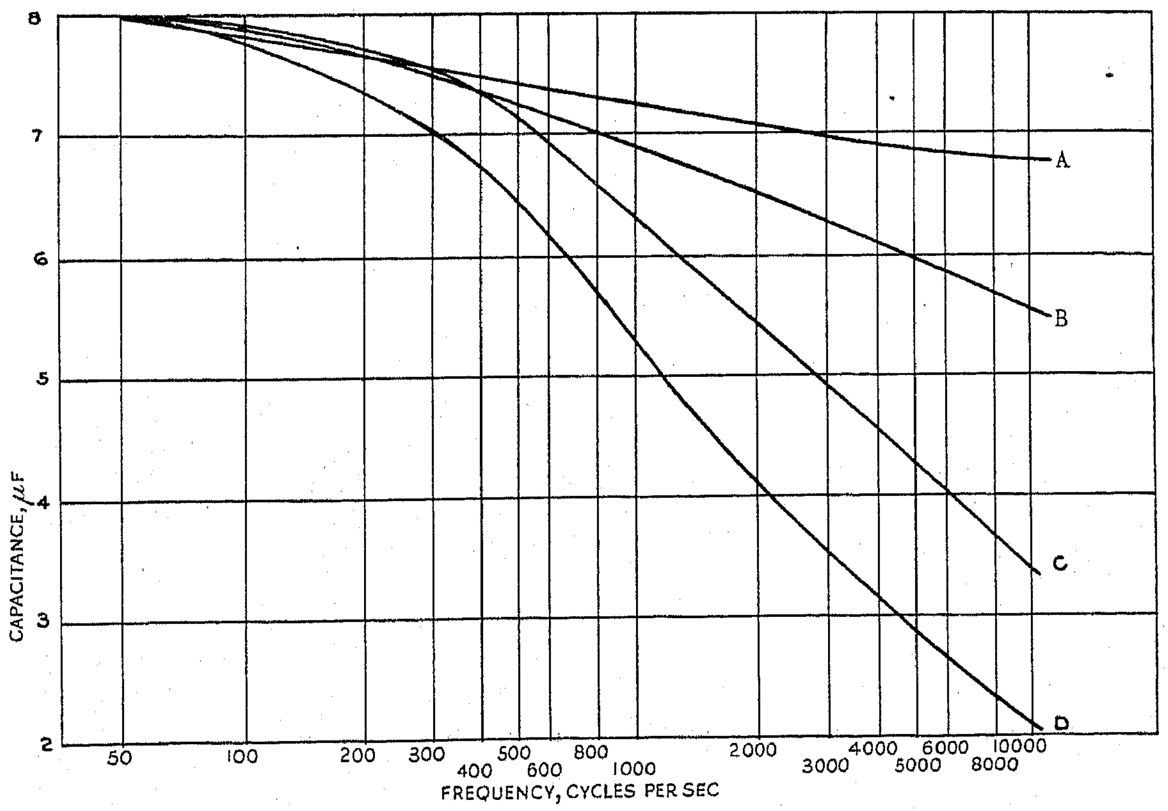

Fig. 20.—Capacitance/frequency relations of wet and dry types of condensers.

Where the fluctuating voltage is considerable, as, for example, in the reservoir condenser following a rectifier, and in the applications of the non-polarized type of condenser in a.c. circuits, it is necessary to ensure that the alternating current through the condenser is not great enough to cause undue temperature-rise. The maximum permissible temperature-rise varies with the condenser, as does the maximum alternating current which should be allowed to pass through it. In general, the larger the bulk of the condenser and the smaller the power factor, the greater will be its volt-ampere rating for ripple current.

(b) For Direct Connection to D.C. Supplies

Where circuits containing electrolytic condensers are incorporated in portable electric or radio apparatus intended for connection directly to d.c. supplies, there is always the possibility of reversal of the connections. In apparatus incorporating a rectifier, such as A.C./D.C. radio receivers and amplifiers, the reverse resistance of the rectifier is sufficiently high to prevent a short-circuit through the electrolytic condenser. In the absence of a rectifier it is necessary to use a reversible or non-polarized electrolytic condenser, or, strictly speaking, a doubly polarized electrolytic condenser. This type has both plates formed, the forming voltage being greater than the maximum possible peak voltage in either direction of connection. As the two film capacitances are in series, two anodes, each of twice the surface area of that used in a singly polarized condenser of the same capacitance, are required. As, moreover, the anode foil is customarily thicker than the cathode foil in the polarized type, the volume of a reversible condenser is rather more than twice the volume of a polarized condenser of equal capacitance and rated voltage. The same electrical effect as that of a reversible condenser may be produced by using two polarized condensers each of the required voltage and double the required capacitance. These are connected cathode to cathode, and the external connections are made to the two anodes. Such a " back to back " connection, however, requires about four times the volume of a polarized condenser of equal rated voltage and capacitance.

(c) For Use in Pure A.C. Circuits

Electrolytic condensers have been used on alternating current alone, principally for split-phase motors. Condensers for this purpose should be of the reversible type, and each anode must be capable of withstanding the peak voltage of the circuit.*

The high power factor of electrolytic condensers, however, makes heat dissipation a very important feature of the design, and it is only practicable to use them for short-period operation, e.g. for motor starting. In the U.S.A., with a majority of 110-volt 60-cycle supplies, such electrolytic capacitors have been widely used. On 200–250-volt mains there are two sources of difficulty which tend to limit their usefulness. Firstly, for a given size of condenser plate at a given frequency, the impedance rises directly as the voltage rating, while the power loss increases as the square of the voltage divided by the impedance. In effect, therefore, the power loss for a given volume of electrolytic condenser increases as the voltage of operation. This means that the condenser has to be limited to shorter periods of operation or the bulk has to be increased for adequate heat dissipation. Secondly, their use at higher voltages than 120 V requires the use of thicker separators between the plates and so further increases bulk and cost.

The use of electrolytic condensers in a.c. circuits is a modern application of an old idea. In 1891 Hutin and Leblanc patented a split-phase motor to operate from single-phase alternating current by the use of polarization batteries, while Mascart and Joubert showed that a polarization battery was equivalent to a condenser.

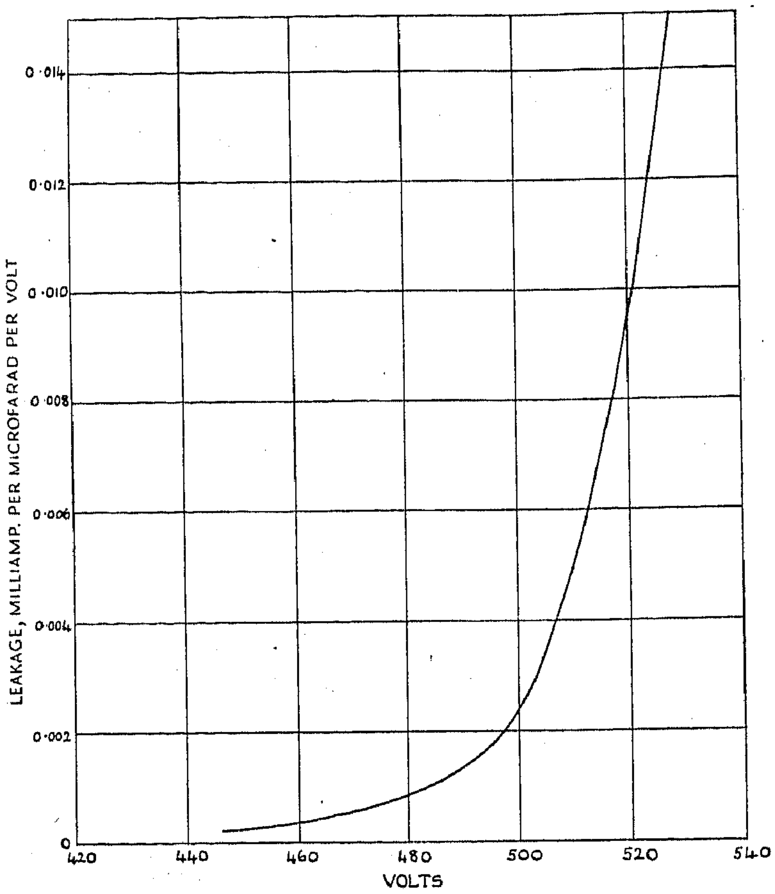

Fig. 21.—Characteristic of " regulating " type condenser.

(d) " Regulating " Condensers

Reference has already been made to the use of condensers for limiting the voltage-rise in a rectifier circuit with poor regulation. Wet electrolytic condensers are used for this purpose, and depend for their operation on the fact that the d.c. leakage current rapidly rises as the voltage is raised above the normal operating point.* If it is raised far enough there may even be sparking at the anode. When the voltage is reduced to normal, however, the condenser functions again in the normal way owing to the self-healing properties of the film. If the condenser is operated too often in this way, the effective life will be shortened, because of excessive evaporation caused by increased leakage and overheating. In addition, there is increased risk of corrosion at the boundary surface once part of the anode is exposed above the level of the electrolyte. A typical leakage curve of a regulating condenser is reproduced in Fig. 21.

It is interesting to consider the location of a regulating condenser in a rectifier system including a choke-condenser filter. The output of the filter is the logical place, because, owing to the added d.c. resistance of the low-frequency choke or chokes, a lower voltage is obtained for a given a.c. input to the rectifier and a smaller leakage current is required for a given reduction in voltage than if the regulating condenser were used as the reservoir condenser immediately following the rectifier. The design of some receivers, however, modifies this, and where they are employed it is more customary to put regulating condensers into the reservoir position.

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* See Bibliography, (58).

* See Bibliography, (62).

ADDENDUM TO SECTION (6)

(*Received 24th May*, 1939.)

(e) Surge-proof and other Special Types of Electrolytic Condenser

Mention has been made in the body of the paper [Section 6(*d*)] of the regulating action of the "wet" types of electrolytic condenser. This is referred to also as a "surge-limiting" action, since it serves the purpose of limiting the rise of voltage across the condenser terminals due to surges, such, for example, as during the heating-up period of the valves in a radio receiver.

With a dry electrolytic condenser no such action is possible to anything approaching the same degree, so that to enable the condenser to withstand these switching-on surges the voltage rating of the normal dry condenser must be made at least equal to the highest peak voltage of the surge.

The "surge-proof" type of condenser is a species of intermediate form, as far as action is concerned, although in construction it is essentially of the dry type. These condensers can, however, withstand the application to them of voltage surges frequently of as much as 30 % above their normal rated working voltage without damage, provided that their duration is limited to, say, less than 60 sec. and they are only repeated at infrequent intervals—say, exceeding an hour. In size they are smaller, and in cost cheaper, than the normal-type dry condensers for the peak voltage rating, and this constitutes their main advantage. These properties are secured by the use of a thicker separator, which is subdivided into at least two layers, and often has at least one of these layers of a more solid structure than the very absorbent paper tissues now generally employed for dry condenser separators. The separator may consist of two paper layers each 0·004 in. thick or thereabouts, or of one layer of paper and one layer of a cellulose ester film—such as "cellophane," or the like. A very usual rating for these condensers is 450 volts (peak) working, 600 volts surge.

Some manufacturers of these condensers have claimed advantages arising from special formation or ageing treatments intended to modify the shape of the reforming characteristic of these condensers. These changes, however, have usually little effect upon the performance of the condenser under surge conditions. The separator construction is a much more important factor.

In addition to the etching processes, of which mention is made in Section 5(*a*), for increasing the capacitance per unit area of the anode, other constructions have been developed for achieving a similar result. One such consists of covering the anode foil with a layer of small metal (aluminium) particles, sprayed on to it, so as to present an enlarged surface area to the electrolyte.

In another construction, usually referred to as a "fabricated anode," the aluminium particles are sprayed on to the surface of a fibrous separator, such as cotton gauze, so as to give a large-area rough metal surface attached to one side of the separator. The capacitance gain per unit area can be made somewhat larger than is normally obtainable with either etched or mechanically treated anode foils, so that a condenser of somewhat further reduced size becomes possible.

(7) ACKNOWLEDGMENTS

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APPENDIX

Standard Specification for Performance and Acceptance Tests

(i) General.

All tests shall be carried out in normal laboratory atmospheric conditions at an ambient temperature lying between 15° C. and 20° C. Condensers shall be mounted or held in their normal working positions for all tests. Wet-type condensers should be upright.

(ii) Re-forming.

Condensers as received shall be subjected to an initial re-forming treatment consisting of the application to them of a steady d.c. voltage equal to their rated working voltage, applied in the correct direction in accordance with the terminal marking. The duration of this treatment shall be as shown in Table 1.

Table 1

Condensers tested	Duration of treatment	
	Dry-type condensers	Wet-type condensers
	min.	hr.
Within 1 month of manufacture	10	2
After 6 months' shelf " idling "	30	6
After 12 months' shelf " idling "	60	12

At the end of this period the leakage current passing through the condenser shall be measured by an appropriate milliammeter, and shall not exceed the following limits, except that in no case need the leakage be less than 0·1 mA:—

Dry-type condensers, 0·15 microamp. per microfarad per volt.

Wet-type condensers, 0·35 microamp. per microfarad per volt.

(iii) Capacitance.

(*a*) *Electrolytic condensers rated for use on direct current.*—The capacitance of the condensers shall be measured at a frequency of 50 cycles per sec. using the impedance method, a bridge circuit, or other equivalent network. For the purposes of this test the condensers shall be subjected to a d.c. polarizing voltage of 75 % of the rated (peak) working voltage of the condenser, while the a.c. ripple voltage (r.m.s.) superimposed thereupon for the purposes of the measurement shall not exceed 10 % of the rated (peak) working voltage of the condenser.

The capacitance value so determined shall not differ from the nominal capacitance value of the condenser by more than the tolerance given in Table 2.

Table 2

Rated voltage of condenser	Maximum permissible tolerances	
	−	+
Up to 100 volts	10	100
Over 100 volts	10	50

(*b*) *Electrolytic condensers rated for use on alternating current.*—The capacitance of the condensers shall be measured at their rated frequency (usually 50 cycles per sec.) using the impedance method, with a voltage, of substantially sine wave-form, of 0·8 of the rated r.m.s. voltage of the condensers applied for a period of 3 sec. The apparent capacitance at the end of this period shall be taken as the capacitance of the condenser, and shall not differ from the nominal capacitance by more than − 10 % or + 25 %.

(iv) Power factor.

This shall be determined by a bridge method with a testing frequency of 50 cycles per sec. and may conveniently be measured at the same time as the capacitance value if suitable apparatus is employed. The value should not normally exceed the limits shown in Table 3.

(v) Insulation.

Where the condensers are enclosed in insulating cases, or in metallic cases but insulated internally therefrom, an insulation test shall be applied between the condenser sections and the metallic case, or between the sections and a metal plate on which the insulating case is laid. This test shall be applied also between any separate condenser sections which are intended to be completely isolated from one another. It shall *not* be applied between the terminals of any condenser sections which have any common connections (either positive or negative) between them.

Table 3

Rated working voltage (in volts) of condenser	Maximum power factor (per cent) for:—	
	Wet-type condensers	Dry-type condensers
Below 50	—	20
Between 50 and 100 ..	—	15
Between 100 and 450 ..	20	10
Over 450	25	10

The insulation resistance when measured with a testing voltage, applied in the above way, of 1 000 volts (d.c.), shall exceed 100 megohms.

(vi) Extra tests.

In those cases where comparisons of a more critical nature are desired as between batches or types of condensers, the foregoing tests may be amplified by the addition of tests of re-forming characteristic and of voltage characteristic, both taken after the application to the condenser of its rated working voltage for a period of 100 hours, followed by an idling period of 100 hours immediately preceding the tests.

DISCUSSION BEFORE THE WIRELESS SECTION, 1ST FEBRUARY, 1939

Dr. F. C. Stephan: In the paper it is mentioned that Betz found that of the oxygen evolved during the forming process by Faraday's law only about 5 % went to form the film, and Güntherschulze and Shipley state that under conditions of sparking in an aqueous electrolyte the volume of gas may be as much as 10 times greater than that given by Faraday's law. A better picture of the forming process and the general behaviour of an aluminium anode in an aqueous electrolyte is given by the results of certain unpublished experiments carried out in the T.C.C. research laboratories. The gases evolved during formation were collected, measured, and analysed, at the anode and cathode, using aluminium electrodes and the usual aqueous solution of ammonium borate. A variable resistor in the circuit kept the current constant, the p.d. across the cell being allowed to rise. On making the circuit, gases were at first evolved at both anode and cathode, as might be expected, since at this stage the anode had no blocking oxide film. Very soon, however, practically all gas evolution ceased at the anode, whilst hydrogen was evolved in a regular manner at the cathode. This condition persisted until the voltage was high enough to cause sparking at the anode. At this point there was a sudden and great increase of gas from the anode, with steady evolution of hydrogen from the cathode. The gases collected now from the anode were no longer oxygen, but a mixture of oxygen and hydrogen accompanied by traces of ammonia and nitrogen. Whereas prior to the onset of sparking the evolution of hydrogen and the absorption of oxygen by the aluminium to form the oxide agreed with the figures calculated from Faraday's law, the gas evolved during sparking was greatly in excess of theory. I think it is obvious that the disruptive action of the sparks on the aqueous solution is the cause of the violent evolution of gases from the anode.

The re-forming characteristic is, as the authors suggest, a measure of the film stability, but it would be preferable to refer to the effect as due to the solubility of the oxide film in the electrolyte. The oxide-dielectric film is soluble in exceedingly minute but measurable quantities in electrolytes, with a minimum solubility at *pH* 7. This is general for all types of electrolytes used in electrolytic condensers, the relative amount, of course, varying somewhat with the actual solution used. The idling properties of a given type of film can be predicted from a study of the electrolyte. The whole theory and practice of electrolytic condensers is bound up with the electrolyte, and many workers neglect the profound influence of the electrolyte on the operation of a condenser.

With regard to Fig. 17, this would be more useful if the capacitance were shown as a percentage of the initial value rather than of the rated value. If this were done the superiority of the wet type would be seen at a glance. Perhaps the authors can give some reason for the sudden increase in the capacitance shortly after the commencement of the life curves of the dry types.

Dr. W. Hackett: The voltage suggested in the proposed specification for the measurement of insulation resistance between terminals and case [Section (v) of the Appendix] would appear to be higher than that often employed on other types of condensers. On the other hand, no provision appears to be made for a proof test between terminals and case, and it would be interesting to know whether such a test is considered unnecessary or whether the insulation test is intended to cover such a test. Since the maximum possible working voltage on an electrolytic condenser is of the order of 500 or 600 volts, presumably the suggested test voltage of 1 000 volts would be adequate.

It is intimated in the paper that the electrolytic condenser can be envisaged as a network consisting of a resistance, corresponding to the electrolyte, connected in series with a parallel capacitance and resistance. It would be interesting to know how far such a network really simulates the behaviour of the condenser in practice, and what proportion of the losses are to be attributed to the electrolyte. The magnitude of the effective capacitance of a condenser represented by such a network would appear to depend to some extent on the function of the condenser in the circuit. For instance, the equivalent parallel capacitance would appear to give the effective value for a filter component, whereas the equivalent series capacitance would give the effective value for a reservoir condenser. The value of capacitance estimated from the impedance measurement would appear to over-estimate the equivalent parallel capacitance and under-estimate the equivalent series capacitance by a proportion equal to half the square of the power factor. For the maximum permissible power-factors suggested in Table 3 of the Appendix, however, the error is probably, in general, unimportant in view of the tolerances normally allowed on the capacitance of electrolytic condensers.

Dr. R. C. G. Williams: The application of electrolytic condensers to radio and television sets is twofold: first of all, there is the reservoir condenser forming part of the main smoothing equipment, and secondly there are the tubular condensers which act as by-pass condensers at the audio-frequency end, where a good low-frequency response is essential.

Dealing first of all with the reservoir condenser, set makers have for some years been paying a considerable amount of attention to the question of whether a dry or a wet type of electrolytic should be used. Some 6–7 years ago the usual procedure was to employ a very large paper-dielectric condenser, and later the wet type of electrolytic condenser came into use. It suffered from certain disadvantages, the chief being leakage of the electrolyte. The dry type of electrolytic condenser was not subject to that difficulty, but in many cases it was unreliable. Since then the dry type has been developed to a very large extent, particularly in the direction of the production of the surge-proof condenser, which embodies many of the advantages of the wet type; but the experience of many set makers to date, so far as their service returns go, is that the wet electrolytic condenser is rather more reliable as a reservoir condenser than the dry. It is difficult to see why this should be so, because the dry type would seem to have all the advantages of the wet and, in addition, the big advantage of lower price and greater compactness. The explanation may be that a wet electrolytic condenser requires less skill in assembly than a dry, so that with the latter, a sudden production rush may turn out condensers which will give trouble after several months' service. Do the authors feel that in the course of years the dry electrolytic condenser is likely to become as reliable as the wet?

Secondly, dealing with tubular paper-dielectric condensers, these are a very cheap and convenient way of getting large capacitances compactly under the chassis of a radio set. It occurs to me that if only we could get over to some extent the disadvantage of the electrolytic condenser in the shape of its lower power factor and higher leakage, a small electrolytic condenser might take the place of a large number of paper tubular condensers such as are at present in use. I should welcome the authors' opinion on this point.

Mr. C. H. Starr: It is sometimes suggested that condenser makers have difficulty in adapting their products to meet the rapidly changing requirements of users. I have here a purchasing specification which we prepared over 3 years ago. It is only recently that it has been necessary to revise it, chiefly owing to advances offered by the condenser makers themselves. The specification runs into some 18 pages, whereas I notice that the standard specification given by the authors at the end of their paper takes up a little under a page of print. Perhaps an 18-page specification is the sort of thing a user would write, whereas the authors' specification is the sort which a supplier would be expected to draw up! The point is that work done in standardizing one's requirements and setting them down in a good specification is of real value to both buyer and supplier.

I notice that Table 1 gives a much longer re-forming time for wet-type than for dry-type condensers, and I should like to know why that is so, when the leakage limit for the wet is already higher. I think that the tolerances shown in Table 2 are rather large, particularly on the high-voltage condensers. I should like to know why these limits are set according to voltage only.

As regards Table 3, I have never been able to understand why anyone should be particularly interested in the power factor of electrolytic condensers, at least so far as their use in ordinary radio smoothing circuits goes.

Mr. W. E. M. Ayres: It has been suggested that a polarization cell in the form of an electrolytic condenser should be used as a phase advancer, connected across the slip-rings of a.c. motors. Some years ago I had to investigate this suggestion and found that the phase angle could not be more than 45° leading for the symmetrical combination of spongy lead electrodes and dilute H_2SO_4. The maximum voltage was limited to 2·2 volts (peak), and the equivalent capacitance increased rapidly with the voltage up to this limit; also the capacitance increased as the slip frequency was reduced. No dielectric-film theory could be made to fit in with the phenomena observed, and the following theory, which appears to answer completely for this type of condenser, was substituted. It is well known that every solution contains dissociated ions to a degree which maintains equilibrium with the solution pressure. When a current traverses the electrolyte, these ions, positive and negative, migrate towards the cathode and anode respectively, building up a higher solution pressure at the surface of the electrodes and a V-curve of osmotic pressure in the electrolyte between the two electrodes. The highest pressure gradient, and therefore potential difference, will occur when the maximum current has flowed through the electrolyte, which, of course, is when the current is just changing direction and passing through zero. The current therefore leads by 90°, and a condenser effect is observed. Simultaneously, however, a process of diffusion is going on which depends upon the differences in solution pressure and follows the same laws as the pressure-increase. Moreover, this diffusion is at its highest value when the pressure-difference is at maximum, and the curve representing the diffusion is therefore in phase with the voltage. These two equal components at right angles give a theoretical maximum power-factor of 0·707. Our results showed that a value of about 0·76 was attainable, and the losses represented by the difference could be accounted for.

The above theory will not apply to oxide-film rectifiers. Al_2O_3 is an insulator and a polar molecule, and may be predicted to act as a condenser dielectric in the dry state. Under such conditions it will behave according to the usual geometric laws. These laws will not hold when it is in contact with an electrolyte, however, and the porous nature of the oxide will not account for the higher capacitance. A satisfactory theory has not yet been put forward, but I am inclined to believe that a chemico-physical explanation is more likely to fulfil the requirements than a film theory based on geometrical considerations.

Dr. G. D. Reynolds: I think that the authors' leakage figures for dry-type condensers are rather generous: our own limit is 0·10 μA per μF per volt.

In addition to applying the power-factor test given in the Appendix, it is desirable to take samples continuously, a few at a time, from the bulk production of these condensers and subject them to a specified life test. Our own test is 2 000 hours at 45° C. with 75 % of the rated voltage, the ripple voltage being equal to 10 % of the applied d.c. voltage. At the end of this test we expect the capacitance to be down by not more than 15 %, the power factor to be up by not more than 33 %, and the leakage to be up by not more than 100 %.

It is mentioned in the paper that the electrolyte can be applied either during the winding of the condenser or by winding the unit dry and then impregnating it. Our own finding on life tests is that impregnation after winding does not usually give so good a condenser, and I should like to have the views of the authors on this matter.

Another point is the authors' reference to separators;

at one time we tended to insist on gauze separators because the paper-separator type of condenser did not stand up at all well on life test. In the paper-separator condenser there was a tendency to use too little electrolyte, and on life tests, particularly at 45° C., the power factor of the condenser quickly rose to 2–3 times the initial figure. Nowadays the allowance of electrolyte is more generous, and it seems that the paper-separator condenser is just as good as the gauze-separator type, and quite appreciably cheaper.

There is one aspect of condenser life on which the authors do not touch, and that is corrosion. It is still possible, even on quite reputable condensers, for corrosion of the tab to occur just where it comes out of the separator; eventually the tab becomes open-circuited, presumably in consequence of corrosion at the electrolyte-air-aluminium interface. Another point where corrosion arises is at the joint of the copper wire to the aluminium-foil tab. It is not always practicable to make sure that electrolyte cannot reach the point at which the copper wires are connected to the tab. If any electrolyte gets to that copper-aluminium junction, corrosion and a very high leakage will occur. The American form of construction, where no copper wires are taken into the can, tends to avoid that trouble completely.

Another question which I should like to ask is what degree of purity is required in the aluminium anode. Two or three years ago we had a batch of condensers in which the purity was a little lower than normal, and very considerable corrosion of the anode occurred. Still on the question of purity, I noticed in the film which the authors showed that a good deal of handling occurred, much of it with bare hands. It is the modern practice to avoid touching the anode foil at all with the bare hands, because of the possible acidity of the perspiration.

Mr. H. L. Oura: There are three points which I think might add to the interest of the paper. In the first place, surge-proof condensers are not mentioned, and I feel that an account of their construction and the theory of their operation would be of great interest and value. Secondly, the author makes no mention of the fabricated-plate type of condenser. The third point of interest is the commercial possibility of building up high-voltage—say 2 000- to 5 000-volt—condensers, by connecting electrolytic condensers in series.

Dr. D. N. Truscott: Güntherschulze and Betz* have published a book in which a fairly comprehensive summary of the subject dealt with in this paper is given. They say that as one forms the electrolytic condenser at low voltages in the first place one gets a homogeneous crystalline layer consisting entirely of Al_2O_3. Above the sparking voltage point-by-point breakdown of this film occurs, followed by some sort of burning-up process and the re-formation of a slightly less even film, which is entirely satisfactory as a dielectric. A third type of film is obtained when the aluminium is formed in an electrolyte in which it is partially soluble, namely a porous film which may be very thick, and this is the sort of film which is obtained by the pre-formation process used in manufacture. When the anode is subsequently formed at high voltage in the normal way, the homogeneous crystalline film occurs between this porous layer and the anode surface; this accounts for many of the desirable properties of the pre-formed condenser, inasmuch as the external porous layer acts as a mechanical barrier, and limits the current at breakdown. The authors' statement that, with suitable use, the life of the electrolytic condenser amounts to at least 2 years, appears unduly pessimistic. Very few radio-set manufacturers would be willing to put into their sets a component which would last only 2 years, and I should like to quote an example from our own experience in this connection. In a bank containing four condensers of high voltage, one of them being a reservoir condenser, we had a total of 5 % of failures over a period of 2½ years, and these condensers, of course, were made some years ago. Güntherschulze says that a life of 15 to 25 years may be expected.

Mr. W. J. Sulston: With regard to Dr. Truscott's comments on the life of condensers, it has been found at the Post Office Research Station that the leakage of a condenser increases rapidly as the d.c. voltage applied is increased above about 70 % or 80 % of the rated d.c. voltage. This is indicated for a typical 250-volt condenser in Fig. A. It would be interesting to know whether, if the condenser were used at, say, 70 % of its rated voltage, there would be a perceptible increase in life.

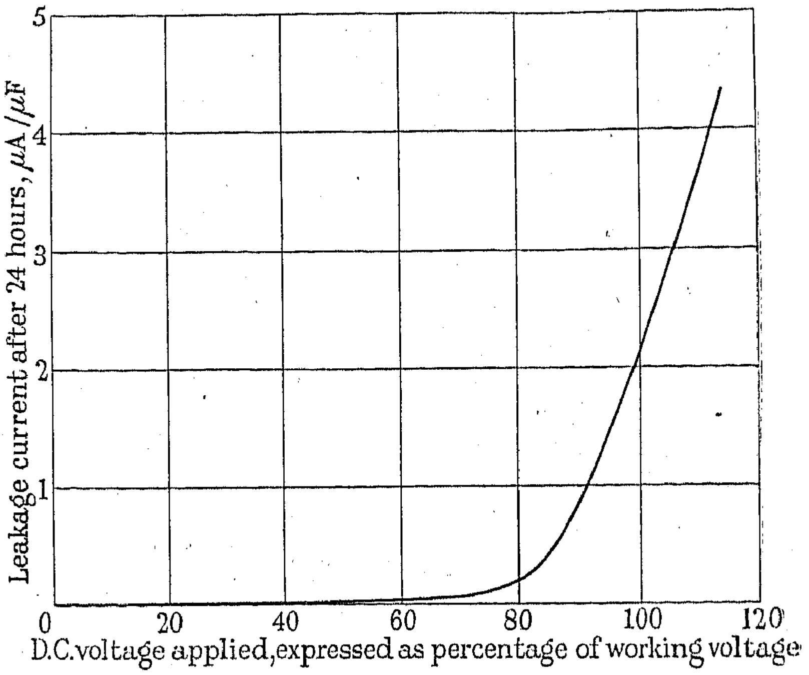

Fig. A.—Variation of leakage current of 250-volt electrolytic condenser with applied voltage.

Mr. Starr criticized the recommendation in Table 1 that treatment up to 12 hours' duration should be applied to wet-type condensers. I should like to suggest that it would be preferable to make the conditioning period independent of the previous life of the condenser, and that this could be done by making it 24 hours in all cases. This is particularly desirable since users do not always know how long has elapsed since the condenser was manufactured, or how long it is since an e.m.f. was last applied to it.

Mr. F. L. Coombs: Fig. 17 shows that the capacitances of dry and wet condensers diminish considerably with time. I should like to know whether the capacitance eventually falls to zero or to a value of the order of, say, 50 %. I ask this question because I think it is important, when considering the design of high-fidelity audio-frequency equipment, to remember that these condensers are used very largely to by-pass the cathode resistance, in order to improve the frequency characteristics at the lower end of the frequency spectrum; and if we cannot rely on getting a high capacitance with an electrolytic condenser, it will be unwise to include it in an amplifier which is expected to give a number of years' service.

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* "Electrolytic Condensers" (M. Krayn, Berlin, 1937).

Mr. E. F. Clark: I should like to ask whether a lower-voltage condenser can be " formed " by a user so that it may be satisfactorily used at a higher voltage.

(*Communicated*) The characteristics of an electrolytic condenser appear to be intermediate between those of an ordinary condenser and those of a battery of accumulator cells. As a user of electrolytic condensers I have come up against the question as to what is the equivalent of an electrolytic condenser in terms of a perfect ordinary condenser of equivalent capacitance and a battery of equivalent coulomb capacity. It appeared that a battery should have a relatively large electrolytic capacitance, yet trial on ordinary frequencies showed this not to be the case.

The final conclusion was that a battery is equivalent to a large electrolytic capacitance together with its known coulomb capacity, both in series with resistance of sufficient magnitude seriously to reduce the smoothing effectiveness of the capacitance; whilst an electrolytic condenser is equivalent to a perfect condenser in series with a very small resistance together with further capacitance plus coulomb capacity, both in series with a much higher resistance. It might be expected, therefore, that the effective smoothing capacitance of an electrolytic condenser at very low frequencies would be greater than that ordinarily measured.

Messrs. P. R. Coursey and S. N. Ray (*in reply*): We are indebted to Dr. Stephan for the account of his experiments, and agree that the abnormal gas evolution only takes place after the onset of sparking. We concur also with Dr. Stephan's estimate of the importance of the electrolyte; that is why we are of the opinion that a theory of operation based on the solid film alone is inadequate.

The solubility of the oxide film is merely a measure in inverse ratio of the film stability. While the electrolyte itself naturally exerts a vital influence on this action, we do not agree that it constitutes the only factor. Different modes of formation of the dielectric film, even when used with the same working electrolyte, can show very different solubilities of the film, as judged by the stability or otherwise of its electrical characteristics.

Fig. 17 was plotted in the manner shown, since the user of the condensers is in general concerned mainly with the actual capacitance value being greater than a certain minimum value which he has allowed for in the design of his filter circuits. The changes with respect to the initial capacitance are therefore of less importance. Dr. Stephan's suggestion concerns only the consideration of the relative properties of the condensers themselves.

The initial rise in capacitance shown by the dry types is very likely to be due to slight voids produced during the impregnation of the section, which are rectified by gradual penetration of the electrolyte into them and possibly also more completely into the interior of the separator fibres themselves. The capacitance thus rises during the early stages of the " run " of the condenser.

In reply to Dr. Hackett, we would point out that a fault in the insulation of the sections of an electrolytic condenser from its metallic case may have two characteristics: there may be a weak part, or fracture of the insulation, due, for example, to mechanical damage; or there may be an excessive leakage over or through the insulation due to its penetration by electrolyte from the sections. The latter type of fault would frequently not be detected by the conventional form of proof voltage test. It is therefore essential to combine that test with some indication of insulation resistance. The most convenient and useful solution results, therefore, in a combined test consisting of the insulation measurement made at the proof test voltage.

We thank Dr. Hackett for drawing our attention to the omission of the capacitance measurements for electrolytic condensers for a.c. circuits. We have made the appropriate addition to Section (iii) of the Appendix.

Measurements of the resistivity of the electrolyte show that this factor accounts for approximately 95 % of the losses in the condenser. This figure has been confirmed also by dielectric-loss measurements on the film itself.* The resistance of electrolytes being a function of the frequency, it becomes impossible to represent an electrolytic condenser by any network having fixed-value components. Attempts have been made in this direction, but without success, even over the audio-frequency ranges.†

The bridge circuit of Fig. 8 measures the " equivalent series capacitance," and, as Dr. Hackett points out, the difference between this value and the apparent capacitance (Fig. 7) and the " equivalent parallel capacitance " is normally quite inappreciable.

The views expressed by Dr. Williams concerning the greater reliability of wet condensers must, we think, have been considerably influenced by different treatments that have often been accorded by the users to the two types of condensers. Any component containing a liquid is naturally given greater consideration and is located in more favourable positions than are others which from their form do not call for any special treatment or handling.

On the other hand, in dry condensers there are many more places during the manufacturing process where incipient faults may occur. One reason is undoubtedly the very small clearances between the film and the cathode in the dry type, clearances which have perhaps been unduly reduced to satisfy the demand for smaller and smaller condensers. Further, owing to the high viscosity of the electrolyte, any undue hastening of the mixing and impregnating processes might cause the formation of local defects. The anode is also subjected to more mechanical handling between " forming " and assembly in the dry type, and there is the possibility of small flaws occurring in the film which may cause failure with a high ripple current such as is associated with a reservoir condenser.

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* H. Zauscher: *Annalen der Physik*, 1935, vol. 23, p. 597.

† N. A. De Bruyne and R. W. W. Sanderson: *Transactions of the Faraday Society*, 1927, vol. 22, p. 42.

It appears that set designers are now using electrolytic condensers wherever these are practicable, and paper (or other dielectric) condensers are only being employed where a variable leak resistance, even of a high value, cannot be tolerated. Small electrolytic condensers have been brought down in size to a point where further reduction in capacitance would be uneconomic owing to the preponderating labour costs, and the space requirements of leads-in and coverings.

In reply to Mr. Starr and other contributors to the discussion, the Appendix has been put forward only as a tentative one. It is very desirable that users and manufacturers should get together with a view to preparing Standard Specifications, and we have made these proposals as covering the essential features which suffice to ensure reasonable uniformity and performance of the condensers. Special requirements of individual manufacturers, such as fixing holes, terminals, etc., have obviously not been included.

Referring in particular to the query raised concerning Table 2, the tolerances are based upon the voltage because the possible uniformity of formation of the film is a direct function of the voltage. The inherent differences in the surface condition of the anode metal cannot be so completely masked by the thin low-voltage film formation as they can by the thicker film formed at higher voltages.

Contrary to Mr. Starr's opinion concerning Table 3, we contend that the power factor of condensers carrying any appreciable ripple current does have an important bearing on their life. Under certain conditions it is also conceivable that the power factor of a condenser by-passing a cathode bias resistance will affect the degeneration or negative feed-back in the amplifier.

Mr. Ayres's remarks regarding the performance of the polarization cell are interesting. We have not referred to this type at any length as these cells are no longer used in practical applications.

We feel that Dr. Reynolds's generalization concerning the impregnation of dry condensers can only have been based upon incomplete data regarding the details of manufacture. Provided that the impregnation is reasonably complete it is immaterial at what stage it is carried out. The " more generous allowance of electrolyte " for paper separators to which he refers is not due to any change of heart on the part of the manufacturer: it is only the result of the development of more suitable material for the separator. A still more generous allowance would be made (and welcomed by condenser manufacturers) if the size and price restrictions imposed by the radio set designers were not so stringent.

For the aluminium anode it is desirable to have metal of a purity of at least 99·85 %. While greater impurity is harmful, a greater purity is not necessarily advantageous from the point of view of performance in service. We agree with Dr. Reynolds that any contamination of the anode, such as by handling, must be scrupulously avoided.

Mr. Oura's request for further information has been dealt with in an Addendum to the paper. High-voltage electrolytic condensers can be built provided that adequate precautions are taken to prevent leakage contact between the electrolytes of the different sections. This can usually be best secured by sealing each section into a metal container which is externally insulated from its neighbours. An increased factor of safety for the voltage rating of each section must be allowed in order to cover inequalities in their leakage.

In reply to Dr. Truscott, the period of 2 years is mentioned as the minimum effective life if the condenser is to retain at least 90 % of its original capacitance. For normal use in radio sets a much greater reduction in capacitance can be tolerated, with its attendant increase of effective life.

We consider that it would be a better description of Mr. Sulston's curve to say that the leakage current falls rapidly if the working voltage is reduced to below 70 % or 80 % of the rated voltage. Under this condition of use the life would be definitely increased.

The fall in capacitance mentioned by Mr. Coombs will certainly continue below 50 %, but in normal conditions many years of service will be obtained before even this figure is reached.

In reply to Mr. Clark, it is unsafe to attempt to " form " up an electrolytic condenser to a voltage higher than the manufacturer's rating. The resulting heating, gas evolution, and exhaustion of electrolyte, will damage the condenser and seriously impair its properties.

DISCUSSION ON "THE MOVING-COIL VOLTAGE REGULATOR"*

NORTH-WESTERN CENTRE, AT MANCHESTER, 15TH NOVEMBER, 1938

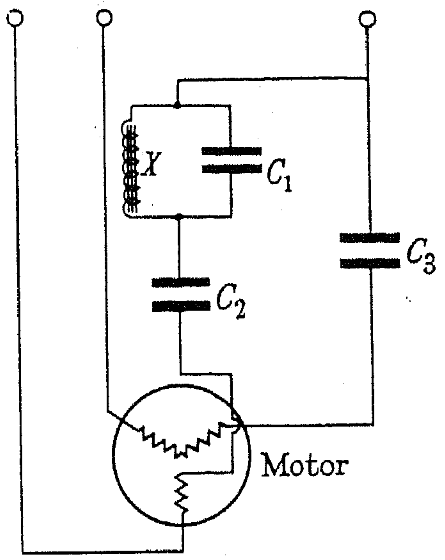
Mr. H. Diggle: The paper describes the practical development of a voltage regulator of a simple type, and gives a very fair statement of its merits and some of its demerits. Its fundamental working principle is seen most clearly in the simplest form (Fig. 1) when it behaves like an inductive potentiometer, in which the moving coil takes the place of the sliding contact of the more usual resistance potentiometer. It must have the usual disadvantages of resistance potentiometers, in that there is no direct transformation effect. There is, of course, a transformation effect between the shunt and the series windings of the types which are shown in the other diagrams, but the statement is, I think, correct in relation to the shunt windings *a* and *b*. With a resistance potentiometer, the no-load current must be chosen at a high value to avoid a high voltage-drop on load, e.g. in the regulator of which the technical data are quoted on page 17 (vol. 83), the no-load current is 1·92 amp. against a winding full-load current of 4·52 amp., i.e. 42 % as compared with approximately 5 % in a transformer regulator. The presence of the large air-gaps, even if worked at low flux densities, would appear to make a high magnetizing current inevitable.

I raised this point in the London discussion, and the author replied that the magnetizing current was not really 42 %, as the full load of the test circuit did not represent the real full-load capacity of the regulator. A second reading of the paper enables me to ask for more precise information on this point. I realize that design proportions could be varied to give relatively low figures if an abnormal amount of active materials were to be used, and also that a regulator with very high magnetizing current might be an advantage in cable-testing equipments to counteract the capacitance loading; but I should like to ask what value of magnetizing current can be expected in a regulator of normal design, expressed as a percentage of the winding full-load current (not of the output full-load current) of a regulator to give, say, ± 10 % boost in, for example, a 300-kVA circuit.

The inherent regulation of the author's voltage regulator would appear to be poor, except when in one of the two extreme positions, and I should like to ask whether the voltage-regulation curve of Fig. 8 with varying lagging power-factors of load will bear the same shape in, for example, the mid-position of the moving coil.

The construction of 3-phase regulators consists simply of assembling three single-phase regulators in one tank. Other types of regulators exist in which it is possible to unite parts of the magnetic circuits so as to achieve reduction in core material and losses, as is done in a conventional 3-leg core-type transformer with common yokes, and I should like to know whether the author has been able to develop any such arrangement for the moving-coil type.

I agree with him in his argument that frequently no good results from a customer specifying too-rapid operation of the regulator to correct voltage fluctuations, and I should like to ask what he considers a reasonable operating speed for an automatic regulator of, say, ± 10 % boost, to cover the whole range under motor drive.



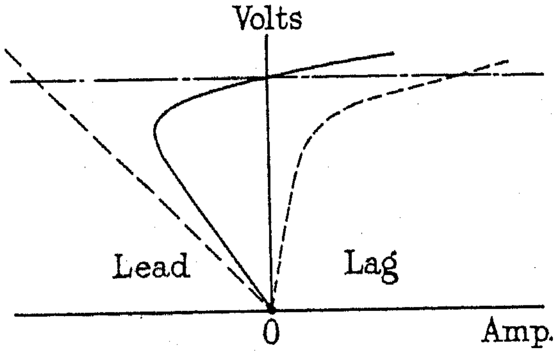


Fig. L

The induction disc motors are, as the author states, inefficient, but the advantage of simplicity of operation may justify their use on small equipments. I submit, however, that it is carrying an idea to extremes to use 8 or 10 of these motors round the periphery of a large gearwheel, as is shown in Fig. 19 (Plate 1). The use of a conventional motor with reduction gearing seems the more logical course, and I note that the latter type of motor has to be used when rapid movement is required. When a large number of small motors has to be used a contactor has to be interposed between the voltage relay and the motors, so that the comparison of Fig. 23, in which the new regulator is shown to have only three links in the chain, as compared with eight for a tap-changer, is exaggerated.

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* Paper by Mr. E. T. Norris (see vol. 83, page 1).

A German manufacturer has gone a step further than the author has envisaged, and produced a system of automatic control in which even the voltage-regulating relay has been dispensed with. A conventional 3-phase squirrel-cage induction motor is split into two circuits as shown in Fig. L, and one winding is connected in series with a " blocking circuit " consisting of a saturated (iron-cored) reactor X in parallel with a condenser C_1. An "adjustment" condenser C_2 is included in the circuit, and a third condenser C_3 is connected in one of the other phases. The resultant current of the " blocking " circuit follows a curve in which the current and voltage are in phase at 100 % voltage, the current changing from " lagging " to " leading " as the voltage varies from higher to lower than 100 % volts. The motor remains stationary at normal voltage, but runs in one direction or the other if the voltage deviates from normal, so that no voltage-regulating relay is required.

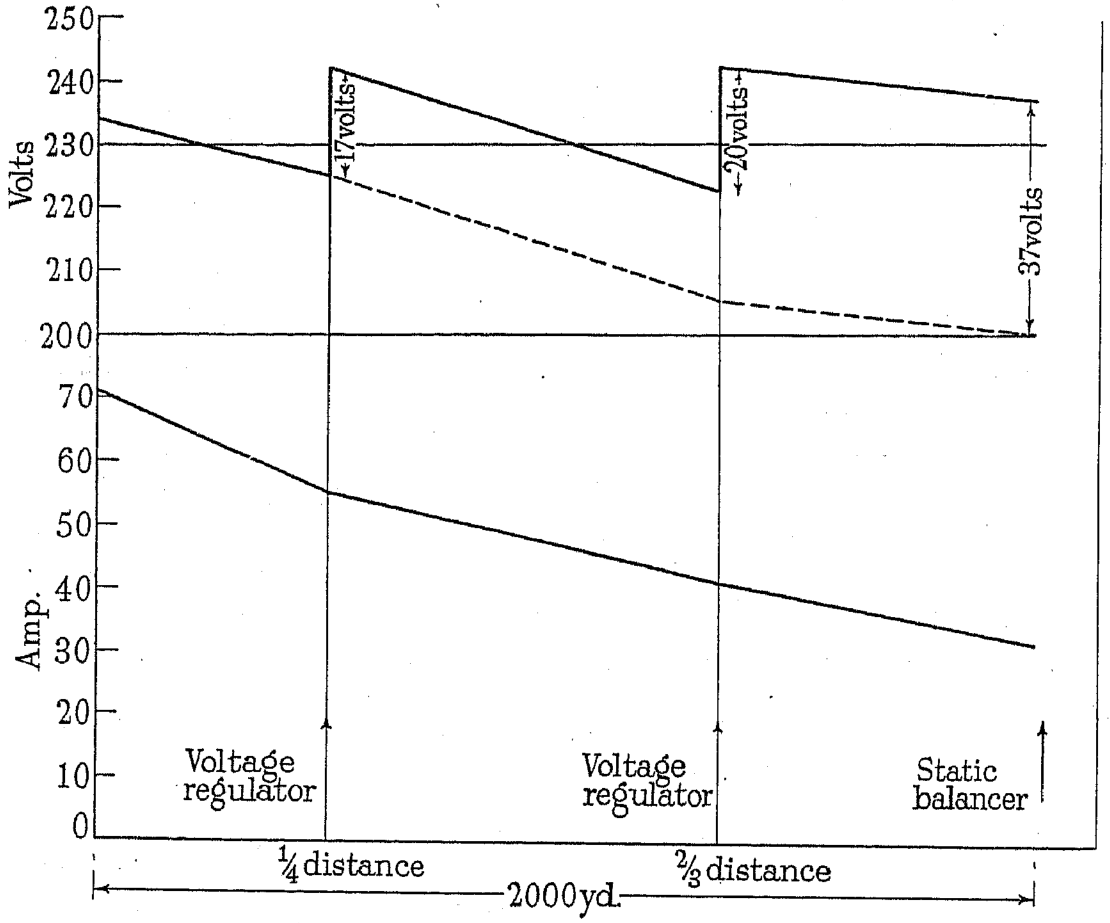

Fig. M.—Voltages and currents at points along 3-phase distributor.

Mr. C. Cameron Kirby: One of the most difficult problems of the distribution engineer to-day, and one that is experienced in a greater or less degree by all public utility undertakings, is to meet economically the requirements of property coming under the head of ribbon development. This problem is more acute with supply undertakings whose areas include suburban and rural districts than with those which are primarily urban in character, and it particularly affects our secondary roads, where development has occurred, sometimes at infrequent intervals, and often without the support of branch roads. Cables laid perhaps 10 years ago when few houses existed have, as a result of this development, proved inadequate to afford a satisfactory supply. At the same time it is often found difficult to determine the best position for a substation to rectify this condition, as the direction in which future development will occur cannot be predetermined. When such conditions obtain, the installation of l.t. voltage-regulating apparatus is of great assistance. It often enables the distribution engineer to delay his selection of a substation site until the load has grown sufficiently to justify it, and to indicate just where it should be chosen.

The undertaking with which I am connected have several similar cases to that just mentioned, and have found a very satisfactory solution along the lines suggested in the paper. In the case of a uniformly loaded distributor the ideal position of the regulator is one-third of the route length from the feeding point. It has been my experience that the full benefits to be derived from voltage-regulating apparatus of this kind are obtained when a static balancer of suitable capacity is installed at the end of the distributor remote from the feeding point. I have found the performance given by moving-coil regulators controlled by astatic relays to be markedly superior to that given by the earlier type of control, and have recently installed the improved relay on the earlier type of regulator.

I recommend distribution engineers who are considering the installation of similar apparatus to specify a switching device for cutting out the regulator without interrupting the supply. Although my own experience has been that the maintenance work on a moving-coil regulator is no more than that required by a transformer, circumstances may arise when it is desirable to switch off the apparatus and still maintain supplies. The most recent regulator supplied to my employers incorporates this feature.

Many voltage-boosting equipments in use to-day have the controlling relay connected across two phases, with the result that all phases may get approximately the same degree of boost irrespective of the loading conditions. For instance, if the incoming low voltages had values such as 220, 230, and 240 volts, then with a 15-volt boost on all phases the outgoing voltages would be 235, 245, and 255 volts. This would not result in satisfactory conditions at consumers' terminals. For an extra charge, separate regulation may be obtained on all phases, and with this arrangement thoroughly satisfactory service will be provided under all conditions of loading. I have had a regulator of this type in service for about 2 years, and its performance has left nothing to be desired. With regard to the relative costs of the moving-coil regulator and competing equipments, the latter have been quoted for at prices from 10 % to 30 % higher for one-relay control, and from 20 % to 70 % higher for three-relay control.

Fig. M indicates a typical problem met with in semi-rural areas. The case illustrated is one of ribbon development, with a distributor some 2 000 yd. in length supplying approximately 50 houses, some 30 % of these being at the extreme end. Prior to the installation of voltage-boosting equipment the supply undertaking was inundated with complaints. Originally one regulator only was installed, but owing to the growth of load a second regulator was connected 2 years later. Since then not a single complaint has been received.

Mr. H. Shackleton: On page 4 (vol. 83), the author refers to the use of a moving-coil regulator to provide smooth voltage variation between tappings of on-load tap-changing equipment. Experience in this district, at any rate, indicates that consumers are not inconvenienced by tap-changes, provided the steps do not exceed 1·5 %. Sudden voltage fluctuations exceeding this amount are frequently experienced at consumers' premises when household appliances are switched on or off. Reduction of contact maintenance is, however, an important point, and anything which enables this to be attained is worthy of consideration, particularly in the case of heavy-current equipment.

I agree with the author in his statement on page 10 that all regulators controlling voltage in distribution circuits should be automatically operated. I have been associated with an undertaking which for the last 5 or 6 years has employed automatic voltage regulation exclusively at all main substations. Records taken over this period indicate the superiority of automatic over manual control. Substation attendants have other duties to perform in addition to controlling the voltage, and even the most conscientious man has to rely on switchboard-pattern voltmeters, which are not usually satisfactory for close regulation. There have been occasions when the automatic feature has had to be cut out temporarily, and at these times there has often been a sharp rise in the number of voltage complaints. Only last Saturday, a complaint was received from another section of the department regarding unsuitable voltage regulation at a certain main substation where automatic control had been dispensed with for a few hours on each of the last few days.

The moving-coil regulator appears to possess several advantages over, say, a tap-changing booster transformer. With the latter, periodical inspection and maintenance are essential for satisfactory working. Although our experience with such equipment has been reasonably satisfactory, troubles have been experienced from time to time. The gear has occasionally failed to complete a tap-change; limit switches have operated and prevented automatic working being resumed until the particular substation has been visited; and excessive arcing on tap-changing contacts has been followed, in isolated cases, by the unit tripping out and causing interruption to supplies.

The noise emitted by the operating mechanism should, in my view, be considered, as well as the noise from the transformer itself, particularly in the case of outdoor installations. Fortunately, complaints of noise have been relatively few. I remember one booster transformer, however, in which the operating motor would have made an admirable air-raid warning siren. The motor eventually burnt out, and the whole gear has since been disposed of.

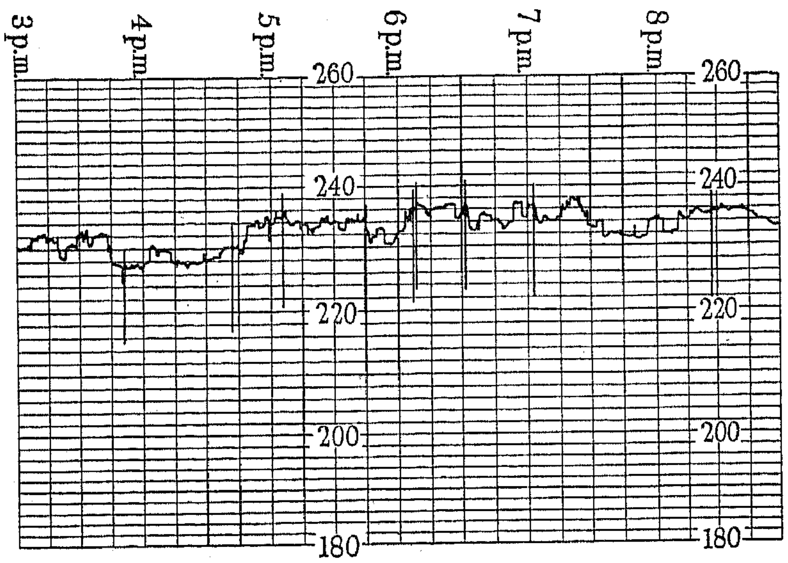

Fig. N

On page 8, transformer noise is stated to be due mainly to core vibration, and therefore occurs at no load but is little affected by load. I would suggest that, in many cases, transformer noise is likely to increase at times of light system load, on account of reduced voltage-drop between the transformer and the generating station.

The omission of control springs and hold-on devices in the astatic relay is a notable advance. The former have given rise to a certain amount of trouble in spite of the manufacturers' assurance that fatigue did not arise, and the latter need very careful adjustment if satisfactory operation is to be attained.

The astatic relay movement is controlled by gravity (which is not likely to alter appreciably) and by the quantity it is designed to control, and appears to eliminate many possible sources of trouble.

On page 13, it is stated that the installation of regulators along the distributor permits loads and feeder lengths which would otherwise result in voltage-drops 4 to 5 times as great. This appears rather optimistic.

Voltage-drop due to switching on apparatus at the far end of a line could be corrected after an interval, but with increased distributor lengths and additional impedance of regulators the initial drop is likely to inconvenience distant consumers. For example, a large milk cooler with a 3-h.p. motor situated some distance from a substation caused voltage "kicks" ranging from 10 to 21 volts on a 230-volt supply, although a 3-phase automatic induction voltage regulator with static balancer was already installed in the distributor concerned. It was found that the starting current taken by the motor varied from very small values up to 40 amp. Voltage fluctuations due to operation of the milk cooler are shown in Fig. N, which is a print of a record taken on the output side of the regulator. Failure of 3-phase regulation to maintain the desired voltage on all three phases is also indicated.

Mr. J. B. Hansell: On page 10 the author refers to a short-circuit test on a regulator, a description of which was given in the *Electrician*. The regulator on which the test was made was designed to give 11½ % boost on a 50-kVA system, and it withstood a short-circuit current of 77 times normal. While this was a severe test, the equivalent kVA of the single-phase regulator on which the test was made was only about 1·9 kVA, and the factor of safety of small transformers and kindred apparatus, against short-circuit forces, is usually very high. The test cannot, therefore, be taken as a general indication of the inherent strength of moving-coil regulator windings.

The coils in the new regulator are long and thin, and one would expect them to offer weak resistance to axial forces.

The author states that the axial force on the regulator winding under short-circuit conditions is reduced by two factors, one being that the change of reactance of the winding, with respect to the movement of the coil, is low. Does not this reasoning apply to axial force on transformer windings when the magnetic centres are displaced? And yet, in the case of a transformer, axial force under short-circuit may be serious on account of the high value of short-circuit current. The force is actually proportional to i^2dL/ds.

When dealing with short-circuit forces, the author states that it is not necessary to protect the regulator windings by means of external series reactors. Apart from the question of short-circuit forces, however, if there is no external reactance in series with the regulator there is the possibility that high voltages may appear on the main windings when a short-circuit occurs on the outgoing side of the regulator.

Fig. O shows a moving-coil regulator designed to give equal positive and negative boosts with the moving coil in the position of zero boost. If a short-circuit occurs on the outgoing side of the regulator and full phase voltage is maintained on the incoming side, this voltage will appear across the boost winding. The voltage on each of the two main windings will be nearly half phase voltage increased in the ratio of turns between the main and boost windings. If this ratio is 20, the voltage across each of the main windings will be rather less than 10 times phase voltage. Fig. P shows the vector diagram of the voltages across the main windings. This condition may be relatively unimportant in low-voltage circuits, but may be serious on systems of 6 600 volts and above. If there is an external impedance in the lines the voltages across the main windings will be reduced.

I should be glad if the author would tell me whether it has been found necessary to increase the insulation on the windings owing to the above possibility, and whether an insulation test higher than the British Standard value is applied to the windings of the regulator.

This condition appears to be analogous to that known as the "inverted neutral," which may occur on a 3-phase system using an auto-transformer booster, unless precautions are taken.

The moving-coil type of regulator seems to have a rather high internal impedance when the moving coil is in the position of zero boost, and in the case of the original design the impedance must have been very high. From the report of the London discussion[*] I see that special compensating windings were used to reduce this impedance on the original design, but were found unnecessary on the new design. A rough calculation seems to show that, for corresponding magnetizing currents, the internal impedance of the new design, with the moving coil in the position of zero boost as in Fig. 1, is about 25 % of that of the old design. I should be glad if the author would tell me whether this is actually the case.

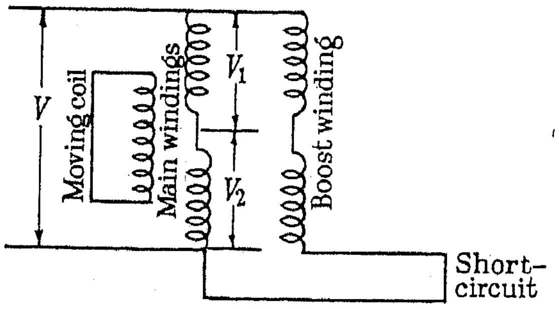

Fig. O

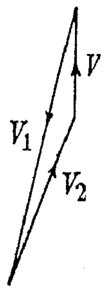

Fig. P

At first sight, the principle of the moving-coil regulator might be thought to be only applicable to very small apparatus; the paper shows, however, that this is not the case, and that this type of regulator has a considerable field of application.

Mr. C. A. M. Thornton: The moving-coil voltage regulator was, I believe, designed primarily for the electric supply industry, but it appears to me that its potentialities for industry in general are not yet fully utilized.

The object of my contribution to the discussion is, by illustrating very briefly how the moving-coil voltage regulator solved one industrial problem, to encourage other industrial uses of this invention. I should like, first, to emphasize the fact that with this regulator one can conveniently and economically obtain any desired voltage over a predetermined range at the outgoing terminals of the regulator, this voltage being only slightly affected by the current load, whatever, within reason, the constant supply voltage may be. For instance, with a supply voltage of 660 volts the secondary-voltage range might equally easily be 0/220, 220/440, 440/770 volts, or any other reasonable predetermined range. Over this range the voltage is infinitely variable.

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[*] *Journal I.E.E.*, 1938, vol. 83, p. 19.

The particular industrial problem in which I was interested was the control of electrical vibrators in a works having feeder cables up to $\frac{1}{2}$ mile in length. This area was covered by a d.c. network only, and the suggestion of the suppliers of the vibrating gear was that local motor-alternators should be put down wherever an a.c. supply was required to feed a vibrator.

It is necessary to describe the problem in some detail in order to demonstrate how the moving-coil-regulator solution emerged. The vibrators consisted of laminated horseshoes, magnetized by a coil, and mounted on the "stator" of the vibrating machinery, each with a laminated armature mounted on the vibrating "deck." "Stator" and "deck" were spring-connected to each other, and both so supported that there was a minimum of interference with the oscillation, while at the same time a minimum of vibration was transmitted to the framework of the building. The vibration produced by such an arrangement is very poor unless the natural resonant frequency of this mechanical system is nearly equal to the frequency of the magnetic impulses.

It will be appreciated that once the mechanical system has been set up it is not easily varied, and therefore it is important that the frequency of the magnetic impulses should also remain constant. Now this is just what one cannot economically achieve with a number of small motor-alternators distributed over a far-flung d.c. network supplying peaky loads. It therefore appeared essential that a central alternator should be installed and efforts concentrated on keeping its frequency constant.

There are several ways of controlling the amplitude of vibration of the system I have described, but the most straightforward is simple variation of voltage at the terminals of the magnet coil. At first sight it might be thought that plain series regulation would be satisfactory and not unreasonably uneconomical, and where the alternator frequency is held rigidly constant this will sometimes be so. In this case the expense of rigid control of alternator speed was considered unjustified, but apart from this a slow drift in the rigidity of encastering of the spring or in the hardness of the spring material will alter the natural frequency of the mechanical system, and therefore alter the current load for a given vibration with constant supply frequency. In addition to this, the amount of the loose load on the vibrating deck may alter the current load of the magnet coil considerably. Now it is important, if the best results are to be obtained from process workers, that a given regulator setting should always produce as nearly as possible the same control.

The series regulator was therefore ruled out, and the choice appeared to lie between the moving-coil regulator and the induction regulator. A moment's consideration will show that the natural power factor of the vibrator described will be low. Vibrations up to $\frac{1}{16}$ in. are generally required, and the air-gap in practice is not less than 0·075 in. Under ideal conditions one cannot hope for a much better power factor than 30 %, and it was obvious that with a load like this it would be difficult to obtain constant voltage at the alternator terminals, let alone at the far end of the a.c. network. It was therefore decided to correct the power factor of each vibrator to unity, as closely as was reasonable, by connecting a condenser across its terminals. For maximum economy it was therefore essential to supply the vibrators at the maximum convenient voltage. It was decided to keep the whole system a medium-voltage system without any transformation by generating at 660 volts (a.c.). The regulators controlling individual vibrators had therefore to be of the "all buck" type, because higher voltages than 660 volts could not be permitted, and the standard design of condenser also was suitable for this voltage. It was this fact that ruled out the induction regulator on economical grounds, because in the size required the two types of regulator were only comparable in cost if the inherent equal boost and buck of the induction regulator could be used.

A large number of moving-coil regulators have now been installed for the above purpose, and have worked very satisfactorily for several years. These regulators have worked satisfactorily both when controlling ordinary alternating current and when controlling alternating voltage with a rectified current load, the current being rectified to halve the frequency of the magnetic impulses that would otherwise have been obtained from the a.c. system. In this latter case condensers cannot be used across the coil terminals to unload the regulator.

There is another industrial application of moving-coil regulators which appears to me to be promising, although I have not yet tried it out. This is the control of current to baths of molten semi-conducting material. Sometimes the bath temperature may have to be kept constant with a constant amount of material in it, but with other factors varying. At other times a constant temperature may be required with varying depths of material. In either case an automatic moving-coil voltage regulator, the motor of which is energized in one direction or the other by high- and low-temperature contacts, would appear to be a solution having certain advantages (e.g. reliability) over other methods.

Mr. A. W. Crompton: The numerous papers on voltage regulation which have appeared in the *Journal* and elsewhere are an indication of the complexity of the problems with which the subject is associated. Prior to the development of the grid system as in 1925,* the range of voltage variation in any particular portion of an undertaking could be ascertained and adequate measures adopted. Present-day conditions, however, render essential on most undertakings the installation of regulators at carefully selected positions on the high-voltage system. The use, in addition, of numerous small regulators at individual network substations, or on low-voltage distributors, should not therefore be conceded unless more radical improvement of the general conditions cannot be adopted because of exceptionally high expenditure having regard to the magnitude of the existing and future loads. Where regulators are employed under such conditions, it is suggested that due regard should be paid to the relative time-lags of the local and main regulators, that of the former being preferably longer. Owing, however, to the deleterious effect of high voltage on the life of lamps and other apparatus, the voltage should be reduced after a shorter time-interval than is occupied in raising the voltage.

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* See the discussion on a paper by Mr. L. H. A. Carr ("The Use of Induction Regulators in Feeder Circuits," *Journal I.E.E.*, 1925, vol. 63, p. 864).

The reference in Section 6(*e*) to the voltage disturbance caused by intermittent loads, indicates the necessity for careful examination of the duties to be performed by plant connected to a low-voltage network. It is therefore very desirable that there should be greater collaboration between the various interests concerned, namely the consumer, the manufacturer, and the undertaking, before such plant is purchased. In many cases it may be found that the only satisfactory means whereby serious interference with the voltage may be avoided is by insisting on a type of drive which does not necessitate the frequent switching in and out of the motor, but employs a clutch or other device so that the motor is not disconnected. The only satisfactory solution in some cases is to provide the supply through the medium of a substation.

Mr. P. Baxter: It seems to me that the application of the author's moving-coil regulator is limited to operation at the ends of feeders rather than close to generating stations, or where high short-circuit currents are possible, because the construction of the regulator does not appear to be such as would withstand these severe conditions. This factor should be borne in mind if it is found necessary to install a regulator at a point where such conditions are possible.

Mr. H. W. Hardern: The author said, in the course of his verbal summary of the paper, that the series reactance of the regulator varied in accordance with the reactance of the two fixed coils taken together in parallel. When the moving coil is at one end, the reactance of the two fixed coils will be in the ratio of 5 to 95, giving a reactance of the two in parallel of rather less than 5 (in arbitrary units); whereas when the moving coil is in the centre, each fixed coil will have a reactance of 50, and the two taken together in parallel will have a reactance of 25 in the same units. Is it correct to assume from this that the series reactance of the regulator varies in the ratio of 5 to 25 according to the position of the moving coil?

Mr. J. Trolan: We have incorporated eight of the author's regulators in a meter-testing equipment which we have constructed—three for voltage control, of 300 VA capacity; two for light-current control, of 300 VA capacity; two for heavy-current control, of 5 kVA capacity; and one 300-VA regulator for general work. We have found these regulators to give very smooth and definite control, and although we use the public supply mains for supplying the equipment the load is exceptionally steady.

I should like to mention a regulator developed in America which gives full automatic control without any relays—a similar sort of arrangement to the one using chokes, condensers, and transformers. The control range is from 95 volts to 125 volts. The output voltage is guaranteed not to vary more than 1 %, but unfortunately the output wave-shape is seriously distorted.

Mr. A. H. Gray: I should like to ask the author whether he finds it necessary to introduce any special anti-hunting feature in this control gear, particularly when high-speed operation is used. The time-delay relay mentioned in Fig. 23 is presumably used to obviate hunting, and it appears to me that if the author omits this relay he will have to replace it by some other device; perhaps he will let us have details of this.

Mr. W. Weston: Whilst it appears convenient to have the motor oil-immersed, is the transformer tank an ideal place for a motor, and is there not a danger of the motor induction disc sticking owing to the settlement of sludge in the oil, or of the bearings being affected by acid? The motors are of comparatively low torque, and one would assume that a comparatively small obstruction would interfere with their working. It is true that this would not result in failure of supply, but it would interfere with regulation, i.e. the very purpose for which the apparatus is provided. Has there been sufficient experience with the apparatus to indicate that trouble of this kind is not likely to occur?

Mr. W. Fennell: I hope there will not be a wrong impression gained, either from the author or from some of the speakers in the discussion, as to the appropriate position for automatic voltage regulators of the type described in the paper. Obviously they cannot be used near the source, and I should like to issue a warning against their excessive use. I look upon automatic regulators as a convenient means for keeping down the number of complaints received from consumers until overloaded systems can be dealt with. Anyone who would lay out a system of distribution which required two or three regulators at different radii from the source, would provide no reserve on the conductors for large changes in load, and those changes are incalculable. The engineer should always put down the largest mains that the estimated demand will support, and then, if events show that he has made an under-estimate, he can carry on with a regulator for a year or so until he can conveniently put the matter right.

Mr. E. T. Norris (*in reply*): Mr. Diggle suggests that if the transformation effect between the shunt and series windings of the regulator is ignored some of the technical characteristics are similar to those of an inductive potentiometer. This is true for the original sandwich construction shown in Fig. 14(*a*) of the paper, where the impedance between the fixed coils "a" and "b" is substantially equal to the sum of the impedances "ac" and "bc" for all positions of the moving coil. For the present construction, however, using concentric coils as shown in Fig. 14(*b*), this relation is not true. The reactances "ac" and "bc" are not bound by the reactance "ab," as explained in Appendix 1 of the paper, so that the regulator has not the limitations of an inductive potentiometer. This matter is referred to in more detail in the reply to Mr. Hardern.

The effect of the air-gap magnetic circuit on magnetizing current is dealt with on page 31 (vol. 83) of my reply to the London discussion. In practice the magnetizing current is so low as to be of negligible importance. For example, in regulators for transmission and distribution circuits actual values are well below those of the corresponding transformer. Since the magnetizing current does not depend upon the variable permeability of iron it can be accurately calculated for any given case, and guarantees can be given within narrow limits.

Actual values for the rating quoted by Mr. Diggle would range from less than 1 % upwards, depending upon the design.

The voltage-regulation curve of Fig. 8 is of the same general shape for all positions of the moving coil, but may be higher or lower in value, depending upon the particular design. A 3-phase regulator consists of three separate single-phase units as shown in Fig. 17, but owing to the magnetic interaction between the phases the fourth yoke of each unit can be omitted as the 3-phase fluxes cancel out. There is therefore a corresponding reduction in core material and losses.

The desirable speed of operation depends so largely upon particular operating conditions that it is not possible to advocate particular values. In general the operating times should be larger for regulators of wide range and for regulators of large capacity. For larger regulators single components of the load will be a small proportion of their total capacity and will not affect the voltage appreciably. Voltage variation therefore will not be erratic but will follow steadily the trend of load increases and decreases, so that longer times of operation are permissible. For many installations, values of 2–8 minutes are quite satisfactory, but the limit in the other direction goes down to a few seconds or less, an extreme example being quoted in the paper, where the time taken to correct a sudden change in voltage of 4 % was reduced to less than 1 second. The use of as many as 8 or 10 motors is exceptional, but I do not agree with Mr. Diggle that even in such cases it is objectionable, as even though a contactor may be required the additional gearing and other complications shown in Fig. 23(*a*) are still eliminated. As an indication of recent developments in regulator construction it may be stated that the regulator shown in Fig. 19 (Plate 1), to which Mr. Diggle refers, if designed to-day would only have 2 motors instead of 8, for the same operating speed. Referring to Fig. L, I would suggest that the reactance-and-condenser combination acts as a voltage-regulating relay, since it is the voltage-sensitive device which initiates the operation of the regulator. The motor is apparently permanently energized and so arranged that a small variation in voltage in either direction results in sufficient change in energy consumption to operate the regulator.

It seems to me that Mr. Kirby has expressed very clearly the economic application of automatic voltage regulation. The addition of voltage regulators and static balancers as the load increases, as shown in Mr. Kirby's Fig. M, results in considerable saving in capital and gives the most economical supply. The Astatic voltage relay is a recent invention referred to only incidentally in the paper, but assists in the simplification of control gear illustrated in Fig. 23. Its main advantages are the elimination of all open contacts requiring cleaning and adjustment, and the absence of control springs and hold-on devices as described by Mr. Shackleton. The need for independent automatic control of each phase, described by Mr. Kirby, depends upon the degree of unbalanced load. Where unbalanced loads are likely, static balancers should be installed. The combination of a standard 3-phase regulator having common mechanical operation of all three phases with static balancers will deal satisfactorily with the majority of ordinary distribution loads. In cases where the degree of unbalance is too great for this arrangement, independently operated single-phase regulators will be required, as suggested by Mr. Kirby. Standard constructions have been developed in which all three units are combined in one feeder-pillar or pole-mounting case.

I agree with Mr. Shackleton that the smooth voltage variation given by the moving-coil regulator is not usually an important advantage, as tapping steps are seldom large enough to be objectionable; but the necessity for operating tap-changing gear in definite steps and ensuring that stopping in an intermediate position is impossible, complicates the control mechanism. The elimination of contact maintenance is also a very important point, as Mr. Shackleton suggests. He reinforces from operating experience the arguments given in the paper for automatic operation of all regulators on distribution circuits. The simplicity and reliability of automatic control is now such that there need be no hesitation in adopting automatic control throughout a distribution network. The noise emitted by the operating mechanism of the regulator is negligible, as the whole of the gear is oil-immersed in the regulator tank, and involves no high rotating speed or reciprocating movements.

The statement on page 13 (vol. 83) that the installation of regulators along the distributor permits loads and feeder lengths which would otherwise result in voltage-drops four to five times as great, is well illustrated by Mr. Kirby's Fig. M. If the dotted-line curve giving the voltages without regulators is redrawn, starting from 240 volts at the substation to represent a regulator at the substation, it will be seen that at the end of the 2 000-yard feeder the voltage-drop would be about 25 volts with a regulator installed in the substation, whereas it does not exceed 5 volts anywhere with the regulators installed along the feeder. Moreover, the diagram shows that the feeder can be extended considerably beyond the 2 000-yard length with satisfactory voltage regulation, giving an even more favourable comparison. Voltage "kicks" due to intermittently operated motors are a difficult problem in distribution networks, and it is fortunate that they are rarely serious enough to cause trouble. I would suggest that the voltage fluctuations are not really as bad as Fig. N indicates; they were due partly to over-run of the recording pen. Consider, for example, the kick at 4.40 p.m. The part of the kick above the voltage line will be due to over-run of the pointer when the motor stops. This amounts to 4 volts. The same pen-inertia would cause 4 volts over-run at the bottom of the kick, so that it may be deduced that the actual voltage kick is only 9 volts and not 17 volts, as is apparently indicated. However, even 9 volts may be objectionable. A voltage regulator will not, of course, remove these kicks, as no regulator is instantaneous in operation.

Mr. Hansell's remarks on the short-circuit tests are answered on page 31 (vol. 83) of my reply to the London discussion. The regulator windings consist usually of single helical or multi-layer coils, which are inherently of great mechanical strength. The basic formula for magnetic forces is the same for regulator windings as for ordinary transformers, as Mr. Hansell suggests, but the actual values are relatively low for the moving-coil regulator, due to the dL/ds values and the neutralization described in Section 4(*d*) of the paper. This matter is discussed further in the reply to Mr. Baxter.

Mr. Hansell refers to the possibility of excessive voltages in the regulator winding when a short-circuit occurs on the output side, giving conditions similar to neutral inversion on a 3-phase system. Fig. P is at first sight somewhat alarming, as it indicates excess voltages approaching infinity for small values of boost. The argument is, however, technically correct only for a dead short-circuit and where there is no external impedance in the supply circuit. Actually, due to the low impedance of the regulator, a relatively small impedance in the supply circuit greatly reduces the value of excess voltage. For example, in the case described by Mr. Hansell where the voltage appears rather less than 10 times the phase voltage (a typical value is 8·5 times), a reactance of only 2 % in the supply circuit will reduce this value to 1·8 times, which as a transient over-voltage is not at all dangerous. Under conditions where the excess voltage would theoretically be higher the effect of external impedance is even greater. Since regulators are usually installed to deal with voltage variations which are caused largely by the supply impedances, excess voltages of this nature are not large enough to need consideration. In the case of a large regulator for relatively high voltage and connected close to a generating station where the supply impedance is below the small value necessary for safety, special consideration would be given to the design and insulation of the regulator. No instance has yet occurred in practice where this consideration was necessary.

The original design of regulator shown in Fig. 14(*a*) of the paper involved higher impedance in the middle position than in the end positions of the moving coil. The special compensating windings were devised to reduce this impedance in the middle position, but were never actually used even on the original design. Mr. Hansell's value of the relative impedances for the two types is typically correct.

Mr. Thornton gives an interesting description of the application of the regulator to the control of a manufacturing process. Modern manufacturing methods have tended towards the use of automatic operation to save labour. Many of these processes and treatments may be electrically controlled, and voltage regulators are in increasing use for automatically controlling power consumption, temperature cycles in heat treatment processes, and many electro-chemical characteristics.

In reply to Mr. Crompton, regulators installed in a high-voltage system can control satisfactorily voltage variations up to the distribution substations, but are limited in the control of voltage-drops occurring nearer to the consumer. These can only be handled by regulators in a distribution network.

In reply to Mr. Baxter, Section 6(*a*) of the paper shows both from theory and from full-scale tests that the moving-coil regulator is mechanically short-circuit proof. Tests were carried out on a standard distribution regulator and were so planned that the short-circuit currents were larger than could possibly occur under operating conditions, even with a power supply of infinite capacity. These conditions are considerably worse than those postulated by Mr. Baxter. A further proof that the mechanical forces are relatively low is that the largest sizes of regulator, as illustrated in Fig. 19, can be operated by induction-disc motors of the type employed for driving gramophones. In actual service a number of cases have been reported of severe short-circuits on large regulators, with satisfactory results. One such instance, involving a regulator of 2 000 kVA, is described by Mr. Peace in the discussion at Leeds (vol. 83, page 29).

The reactance relationship deduced by Mr. Hardern would be correct for the original type of regulator shown in Fig. 14(*a*) of the paper, where the reactance between the two fixed coils is always approximately the sum of the reactance between each fixed coil and the moving coil. For the present construction of regulator using concentric coils, as shown in Fig. 14(*b*), this limitation does not apply, as explained in reply to Mr. Diggle. In the middle position, for example, the reactances "ac" and "bc" are each appreciably less than half of the reactance "ab." The resulting regulator reactance is therefore much lower, as suggested by Mr. Hansell.

The regulator described by Mr. Trolan is apparently one of the saturated-choke type referred to in the fourth paragraph of Section (2) of the paper.

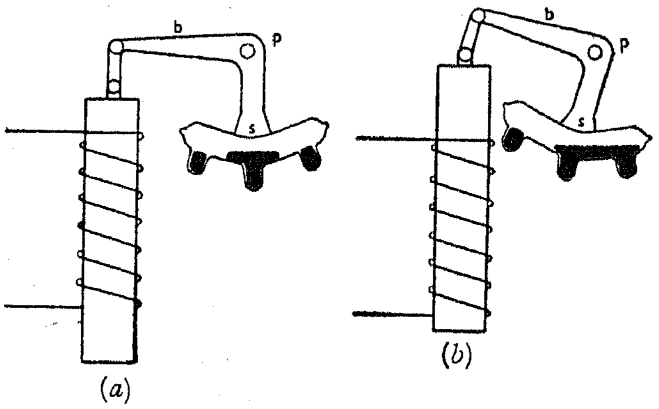

Fig. Q.—Diagram showing the mechanical action of the Astatic voltage relay.

In reply to Mr. Gray, the time-delay relay shown in Fig. 23(*a*) is used partly to obviate hunting but mainly to restrict frequency of operation, so as to reduce wear of motor contactors and tapping-switch contacts. An anti-hunting feature is inherent in the construction of the Astatic voltage relay, providing the automatic operation.

The mechanical action of the relay is shown diagrammatically in Fig. Q, where diagram (*a*) shows the normal balanced position, and diagram (*b*) the operating position for lowering the voltage. Because of the meniscus action of the mercury the tilting angle for opening the circuit when the relay resets is considerably less than the tilting angle for making the circuit, as in diagram (*b*). This difference between the angles of make and break is, of course, an inherent characteristic of a mercury switch and not only results in corrections of voltage variations to values well within the sensitivity range but gives the anti-hunting protection referred to by Mr. Gray.

Mr. Fennell, by looking upon "automatic regulators as a convenient means for keeping down the number of complaints," is considering only one application of regulators, and that of relatively minor importance. The principal use of automatic regulation is to increase revenue* and to reduce capital expenditure on cables, lines, and substations.* This application is well described in Mr. Kirby's remarks, whilst the economics are dealt with later in my reply to Mr. Beckett.

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* F. S. Naylor: "Loss of Revenue on Heating and Lighting Loads, due to Poor Voltage Regulation," *Journal I.E.E.*, 1936, vol. 79, p. 33.

The excessive use of anything is, of course, to be deplored, but the use of automatic regulators in this country, though spreading rapidly, is still so far from its efficient limit that there is as yet little danger of excessive use. With regard to the last sentence of Mr. Fennell's remarks, I would suggest putting down the smallest mains the estimated demand in the near future will require—making economic use of automatic voltage regulators initially, if the growth of load is likely to be small. Then (*a*) the load is not so likely to fall short of the estimate, as in Mr. Fennell's case, and if it does the waste of capital will not be so great; (*b*) if the load develops in accordance with the estimate the distribution costs will be low; (*c*) if and when the load exceeds the initial estimate the growth can be met by installing one, and subsequently two, regulators, as Mr. Kirby suggests and as illustrated in Fig. M. This layout gives the lowest possible cost of distribution; (*d*) if the load should ultimately exceed the range of economic regulator control, additional feeders or substations will then be required. When the load increase is large enough for this change the revenue will justify the additional expenditure, whilst interest and sinking-fund costs on the additional capital will have been saved. The automatic voltage regulators, which should be of standard rating, will then be removed and can be used elsewhere.

In reply to Mr. Weston, it has been common practice for many years to immerse on-load tap-changing gear-operating mechanisms in oil, and experience has shown no deleterious effects. Moving-coil regulator motors have been examined after 7 years in service and have shown no sign of the phenomena mentioned by Mr. Weston.

DEVON AND CORNWALL SUB-CENTRE, AT EXETER, 16TH NOVEMBER, 1938

Mr. D. R. Beckett (*communicated*): Quite early in his introductory remarks, the author stated that the voltage regulator was a cheaper alternative to the crude method of improving voltage regulation by laying additional copper. Crude it may be, but it has the merit of reducing losses, whereas the installation of voltage regulators increases them. When comparing the financial merits of the two systems, therefore, the difference in annual cost between the reduced losses of the additional copper and the increased losses due to the regulator should be worked out, and this figure should be capitalized and added to the initial cost of the latter in order to arrive at a true comparison. Such a comparison may not always be favourable to the regulator.

From this point of view the lack of any information in the paper as to the magnitude of the losses is to be deplored. Whilst I appreciate that losses can vary inversely with capital cost, as in the case of transformers, it still appears to me that a basis can be found for comparison. For every size of transformer to work on a given load factor, the member firms of the Transformer Makers' Association have a standard value of iron loss and of copper loss, on which basis they all quote. Alternative quotations are also frequently given for transformers with reduced losses, at higher prices. Similarly, no doubt the author's firm have standard losses for each size of moving-coil regulator, which they put forward in the absence of any specific demand for lower losses by the prospective purchaser. I therefore ask the author how the standard iron loss and copper loss of a moving-coil regulator for a given through-put compare with the T.M.A. standard iron loss and copper loss of a transformer of the same kVA rating, designed to be used at the same load factor.

When comparing the moving-coil regulator with the induction regulator, the author stated that the former had very much lower mechanical forces on account of its much larger air-gap, this being due to the fact that electromagnetic force is proportional to dx/ds, where x = reactance and s = air-gap. I would point out that the air-gap of an induction regulator remains constant, so that his formula appears to be inapplicable, and in fact something of a red herring drawn across the trail.

In Section 3(*b*) the author states that Type A moving-coil regulators are used as an alternative to chokes or preventive auto-transformers with on-load tap-changing gear. Surely a great reduction in both capital and maintenance costs would ensue if the moving-coil regulator were manufactured as an integral part of the transformer in substitution for the on-load tap-changing gear, having regard to Section 6(*d*) and Fig. 23. Figs. 2 and 5 appear to refer to some such arrangement, yet the author makes no reference to the constructional details of such transformers, neither does one see them mentioned in the technical Press. It would appear, therefore, that some obstacle has prevented the successful exploitation of this idea. I should like the author to state the nature of the obstacle and whether it is being overcome or seems likely to remain insuperable.

Mr. E. T. Norris (*in reply*): I agree with Mr. Beckett that in making comparisons between automatic voltage regulators and cables of larger section the losses of the regulator and the difference in cable losses should be capitalized as he suggests. I do not, however, think that such capitalization will ever affect the conclusion that automatic regulators will be the more economical. This is largely due to the relative costs of regulators and of cables or overhead lines in a distribution network. The proportions are illustrated in Figs. R and S, which are for overhead and underground systems respectively and are based on information given in authoritative Institution papers.* The cost of voltage regulators is comparable with the cost of transformers, so it is obvious from Figs. R and S that this cost is very small compared with the cost of lines and feeders. From these figures it would appear that automatic voltage regulators could be installed throughout a distribution system for an extra cost of less than 1 per cent of the total cost of the supply, this increase taking no account of the advantages of automatic voltage regulation or the savings effected in cables and lines. A typical practical example may be quoted from a paper by Mr. A. C. McQueen (*E.P.E.A. Journal*, November, 1936):—

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* A. C. MacQueen: "Voltage Regulation on the L.T. A.C. Network," *Electrical Power Engineer*, 1936, vol. 18, p. 717.

* E. W. Dickinson and H. W. Grimmitt: "The Design of a Distribution System in a Rural Area,". *Journal I.E.E.*, 1932, vol. 70, p. 189; and J. R. Beard and T. G. N. Haldane: "Design of a City Distribution System," *ibid.*, 1927, vol. 65, p. 97.

"L.T. distribution in a city area: On a 4-core 0·5 sq. in. feeder 300 yards in length, carrying 75 % full load, the voltage drop at the feeding point would be approximately 13 volts between phases. An expenditure of £800 on l.t. cables would only reduce this drop to 6·5 volts, whereas a compounded regulator costing £200 would not only entirely eliminate the voltage drop on the feeder, but could be arranged to compensate for part of the pressure drop on the distribution as the load increased."

If a voltage regulator were installed to give the same voltage improvement as the extra cable section the total capitalized cost based on the grid tariff for bulk supply and on normal distribution conditions would bring the regulator price up to £250–£300, in comparison with £800 for the l.t. cables.

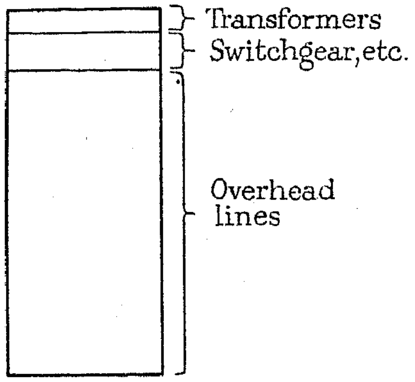

Fig. R.—Capital cost of overhead-line rural distribution system.

The cost and efficiency of the moving-coil regulator in comparison with other types of voltage regulator is dealt with fully in the first five paragraphs of my reply to the London discussion (vol. 83, page 30). The particular comparison asked for by Mr. Beckett is complicated by the fact that the cost and losses of a voltage regulator are not merely a function of its through-put kVA, but depend upon the range of voltage variation and also upon the relative proportions of buck and boost. It is, however, possible to say that for distribution conditions the losses in the regulator are appreciably less than in a standard transformer. The voltage regulator is, in effect, an auto-transformer, with similar reduction in losses due to the auto-connection. For this reason the regulator losses are in general of negligible importance. In any particular case, of course, guarantees of both load and no-load losses can be obtained, as for other apparatus.

The relation between electromagnetic forces and dx/ds is given in my reply to the London discussion, on page 31 of vol. 83. This fundamental relation is the basis of formulae for calculating the electromagnetic forces in transformer windings and circuit-breakers, and on busbars in a static condition.* It is equally applicable to the air-gap of an induction regulator, so that the red herring suggested by Mr. Beckett does not metaphorically exist.

The Type E moving-coil regulator has been used for the purpose described in Section 3(*b*) of the paper. It increases the total cost of the on-load tap-changing gear, as the regulator is more expensive than the choke coil it replaces, and necessitates additional motion in the mechanical operation. The advantage of smooth voltage variation is not usually important in supply circuits, whilst the reduced wear and tear of the switches depends largely upon the current rating, the size of transformer, and the frequency of operation. For large units where automatic control involves frequent operation the Type E regulator would seem desirable.

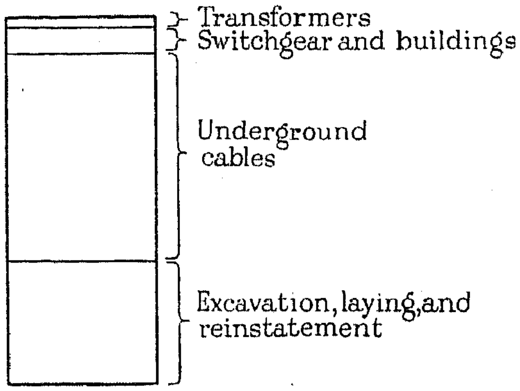

Fig. S.—Capital cost of underground-cable urban distribution system.

The use of the Type A moving-coil voltage regulator instead of on-load tap-changing gear, as shown in Fig. 2 of the paper, is quite practicable and is frequently employed. The total losses will be somewhat increased owing to the regulator, but it has the advantages described by Mr. Beckett. The automatic control is simplified, as described in Section 6(*d*) of the paper, and no periodical shutting-down for cleaning and renewal of switch contacts is required.

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* See J. E. Clem: "Mechanical Forces in Transformers," *Transactions A.I.E.E.*, 1927, vol. 46, p. 577; also H. B. Dwight: "Mechanical Forces on Busbars," *ibid.*, 1920, vol. 39, p. 1337.

HIGH-SPEED OIL CIRCUIT-BREAKERS: INTERPRETATION OF "SINGLE-LOOP" OSCILLOGRAMS*

By E. E. I. PILCHER, B.A., B.Sc.†

(*Paper first received* 5*th April, and in revised form* 16*th May,* 1939.)

SUMMARY

This paper deals with the interpretation of a type of oscillogram which may be obtained in the short-circuit testing of high-speed circuit-breakers. It describes two alternative methods for determining the alternating component of the short-circuit current when interruption occurs at a first zero-current after commencement. Under such circumstances the oscillogram shows only one current "loop" for the phase or phases concerned, and the usual simple method cannot be used. Some method, such as those described in the paper, is desirable for the purpose of framing standard specifications for the testing of high-speed circuit-breakers.

With the development of high-speed oil circuit-breakers capable, in a make-break shot, of interrupting the short-circuit current at a first-zero value, a method is needed for estimating, from the relevant oscillograms, the value of the alternating component of the current interrupted by the breaker. The alternating component is usually estimated by measuring the ordinate between the envelopes of the positive and negative peaks; this ordinate, of course, gives the double amplitude of the component in question. If, however, the current has been interrupted at a first-zero in one phase, the envelopes cannot be drawn, either for that phase or for any other phase, since the current waves in the other two phases will have been distorted from their "balanced three-phase form" by the interruption in the first phase.

Under these circumstances some other method is required for estimating the value of the alternating component of the current; and it is the object of this article to discuss two methods which are available for the purpose. The mathematical analysis on which they are based is given in an appendix. A description of the two methods is given, and this is followed by some examples which serve as illustrations and at the same time indicate the accuracy obtainable. Since the first of the two methods is based on the use of the curves shown in Fig. 1, full data for re-plotting the curves to a larger scale, if desired, are given in Table 1. The method used for calculating the quantities given in Table 1 is illustrated in Table 2. The oscillograms used in the examples are reproduced in Figs. 2, 3, and 4.

METHOD No. 1

This method can be applied to a single-phase oscillogram, or, in the case of a three-phase oscillogram, it can be applied to each phase independently. It is based on a measurement of the time-interval between the inception of the short-circuit and the first subsequent current-zero, and also on a measurement of the intervening peak value. It is, in addition, necessary to know beforehand the power factor of the test circuit; this will, in general, be known to the test engineers from previous records. The time-interval in question is denoted by $r\pi$, that is to say r denotes its ratio to the half-cycle. The peak value of

Table 1

VALUES OF I_a/I FOR VARIOUS VALUES OF r AND κ

r	Values of κ					
	0·00	0·06	0·12	0·18	0·24	0·30
0·4	5·23	5·22	5·18	5·13	5·10	4·97
0·5	3·40	3·40	3·40	3·37	3·31	3·27
0·6	2·43	2·43	2·42	2·39	2·37	2·34
0·7	1·83	1·82	1·82	1·81	1·79	1·77
0·8	1·45	1·45	1·44	1·43	1·42	1·41
0·9	1·185	1·185	1·183	1·178	1·174	1·170
1·0	1·000	1·000	1·000	1·000	1·000	1·000
1·1	0·865	0·866	0·868	0·872	0·876	0·882
1·2	0·764	0·765	0·770	0·778	0·787	0·800
1·3	0·688	0·691	0·700	0·711	0·728	0·745
1·4	0·630	0·634	0·646	0·666	0·688	0·715
1·5	0·586	0·593	0·612	0·639	0·672	0·708
1·6	0·553	0·564	0·594	0·632	0·678	0·724
1·7	0·528	0·548	0·595	0·654	0·711	0·761
1·8	0·512	0·553	0·633	0·717	0·776	0·825
1·9	0·502	0·620	0·746	0·826	0·875	0·904
2·0	0·500	1·000	1·000	1·000	1·000	1·000

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† Metropolitan-Vickers Electrical Company, Ltd.

Table 2

CALCULATION OF I_a/I FOR VARIOUS VALUES OF r WHEN $\kappa = 0{\cdot}24$

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
r	$r\pi$		$\cos r\pi$	$\kappa r\pi$	$e^{-\kappa r\pi}$	$e^{-\kappa r\pi} - \cos r\pi$	$\sin r\pi$	$\tan\theta$ (col. 7 ÷ col. 8)	θ		$\kappa\theta$	$e^{-\kappa\theta}$	$\cos\theta$	$e^{-\kappa\theta}\cos\theta$	$\frac{1}{2}\kappa^2 e^{-2\kappa\theta}\cos^2\theta$	I_a/I
	Rad.	Deg.							Deg.	Rad.						
0·4	1·257	72	0·309	0·302	0·739	0·430	0·951	0·451	24·3	0·424	0·102	0·903	0·911	0·824	0·020	5·10
0·5	1·571	90	0·000	0·377	0·686	0·686	1·000	0·686	34·5	0·602	0·144	0·865	0·824	0·713	0·015	3·31
0·6	1·885	π − 72	− 0·309	0·452	0·636	0·945	0·951	0·994	44·8	0·782	0·188	0·829	0·710	0·588	0·010	2·37
0·7	2·199	π − 54	− 0·588	0·528	0·590	1·178	0·809	1·455	55·5	0·968	0·232	0·793	0·566	0·448	0·006	1·79
0·8	2·513	π − 36	− 0·809	0·604	0·546	1·355	0·588	2·305	66·5	1·161	0·279	0·756	0·398	0·301	0·003	1·42
0·9	2·827	π − 18	− 0·951	0·678	0·506	1·457	0·309	4·72	78·0	1·361	0·327	0·721	0·207	0·149	0·000	1·174
1·0	3·142	π	− 1·000	0·755	0·470	1·470	0·000	∞	90	1·571	0·377	0·685	0·000	0·000	0·000	1·000
1·1	3·456	π + 18	− 0·951	0·828	0·437	1·388	− 0·309	− 4·495	π−77·4	1·79	0·430	0·650	− 0·217	− 0·141	0·000	0·876
1·2	3·770	π + 36	− 0·809	0·906	0·404	1·213	− 0·588	− 2·060	π−64·1	2·02	0·486	0·615	− 0·437	− 0·269	0·002	0·787
1·3	4·084	π + 54	− 0·588	0·972	0·378	0·966	− 0·809	− 1·194	π−50·0	2·27	0·545	0·580	− 0·642	− 0·372	0·004	0·728
1·4	4·398	π + 72	− 0·309	1·055	0·348	0·657	− 0·951	− 0·690	π−34·6	2·54	0·610	0·543	− 0·823	− 0·447	0·006	0·688
1·5	4·712	π + 90	0·000	1·130	0·323	0·323	− 1·000	− 0·323	π−17·9	2·83	0·680	0·507	− 0·952	− 0·482	0·007	0·672
1·6	5·026	− 72	0·309	1·206	0·299	− 0·010	− 0·951	+ 0·0105	π+0·6	3·15	0·756	0·469	− 1·000	− 0·469	0·006	0·678
1·7	5·340	− 54	0·588	1·281	0·278	− 0·310	− 0·809	+ 0·383	π+20·9	3·51	0·842	0·431	− 0·934	− 0·402	0·005	0·711
1·8	5·654	− 36	0·809	1·357	0·257	− 0·552	− 0·588	0·938	π+43·2	3·89	0·934	0·392	− 0·729	− 0·286	0·002	0·776
1·9	5·968	− 18	0·951	1·433	0·238	− 0·713	− 0·309	2·310	π+66·6	4·31	1·034	0·355	− 0·397	− 0·141	0·001	0·875
2·0	6·283	0	1·000				− 0·000	∞	π+90				0·000	0·000	0·000	1·000

NOTE.—The values in col. 17 = 1/(1 − col. 15 + col. 16).

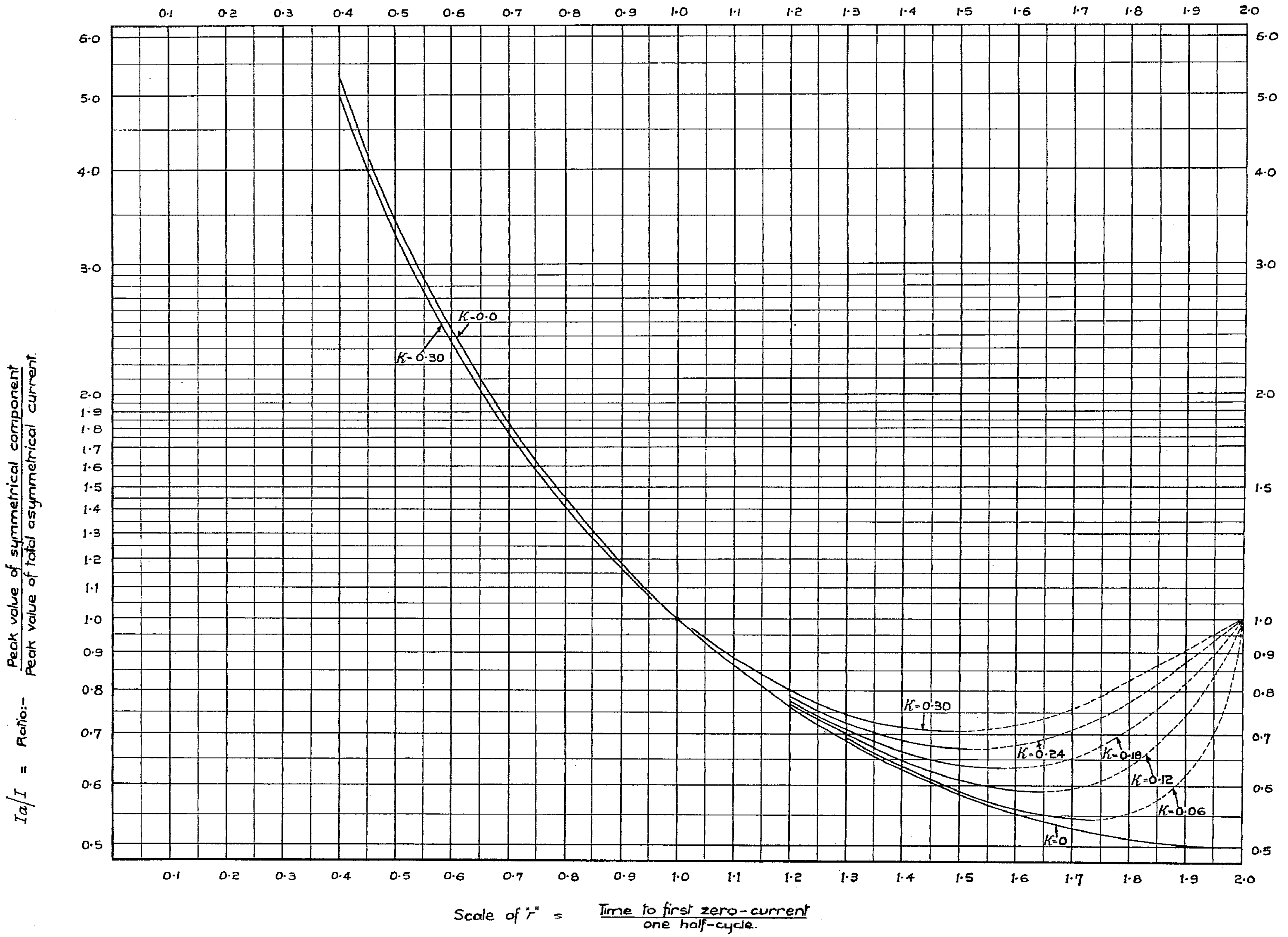


Fig. 1.—Curves for determining the symmetrical component of an asymmetrical short-circuit current, given the power factor and the time interval between commencement and first zero-current, in terms of its ratio to the half-cycle. The value of κ is approximately equal to the power factor × 0·925.

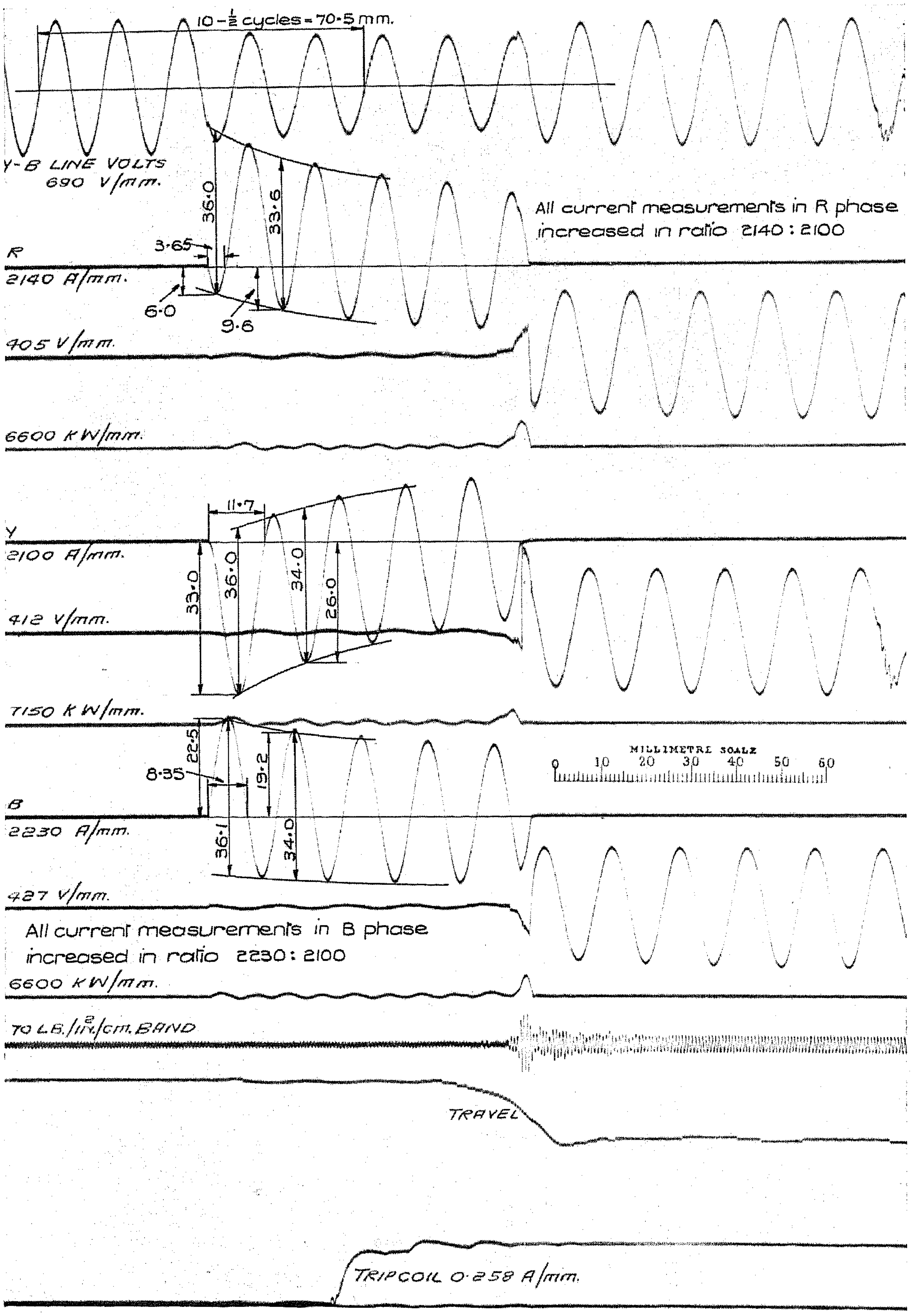
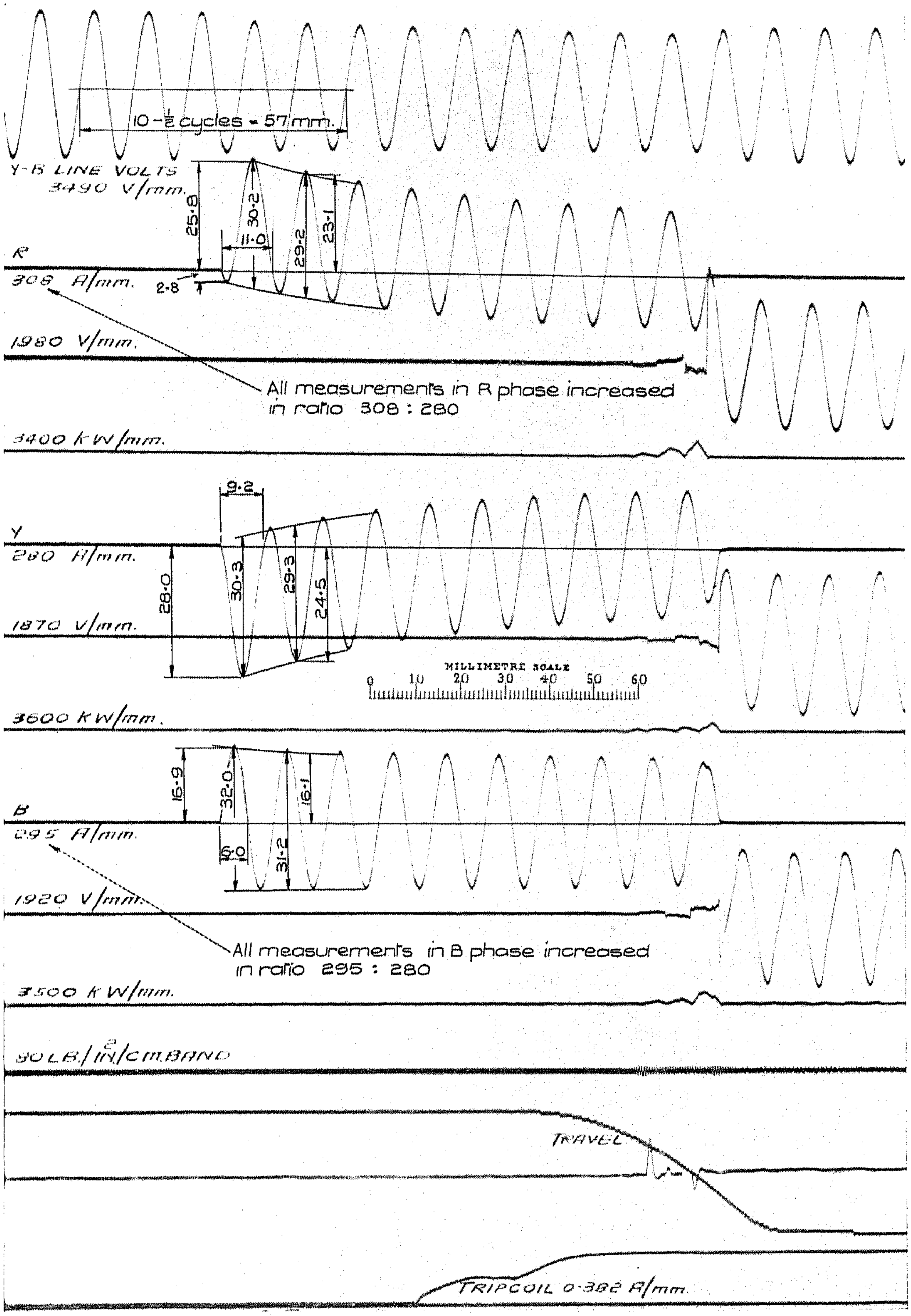

10-½ cycles = 70·5 mm.
Y-B LINE VOLTS
690 V/mm.
36·0
33·6
3·65
R
2140 A/mm.
6·0
9·6
All current measurements in R phase
increased in ratio 2140 : 2100
405 V/mm.
6600 KW/mm.
11·7
Y
2100 A/mm.
33·0
36·0
34·0
26·0
412 V/mm.
7150 KW/mm.
22·5
8·35
19·2
MILLIMETRE SCALE
0
10
20
30
40
50
60
B
2230 A/mm.
36·1
34·0
427 V/mm.
All current measurements in B phase
increased in ratio 2230 : 2100
6600 KW/mm.
70 LB./IN.²/CM. BAND
TRAVEL
TRIPCOIL 0·258 A/mm.

Fig. 2



All measurements in R phase increased in ratio 308 : 280

All measurements in B phase increased in ratio 295 : 280

Fig. 3

Plate 4

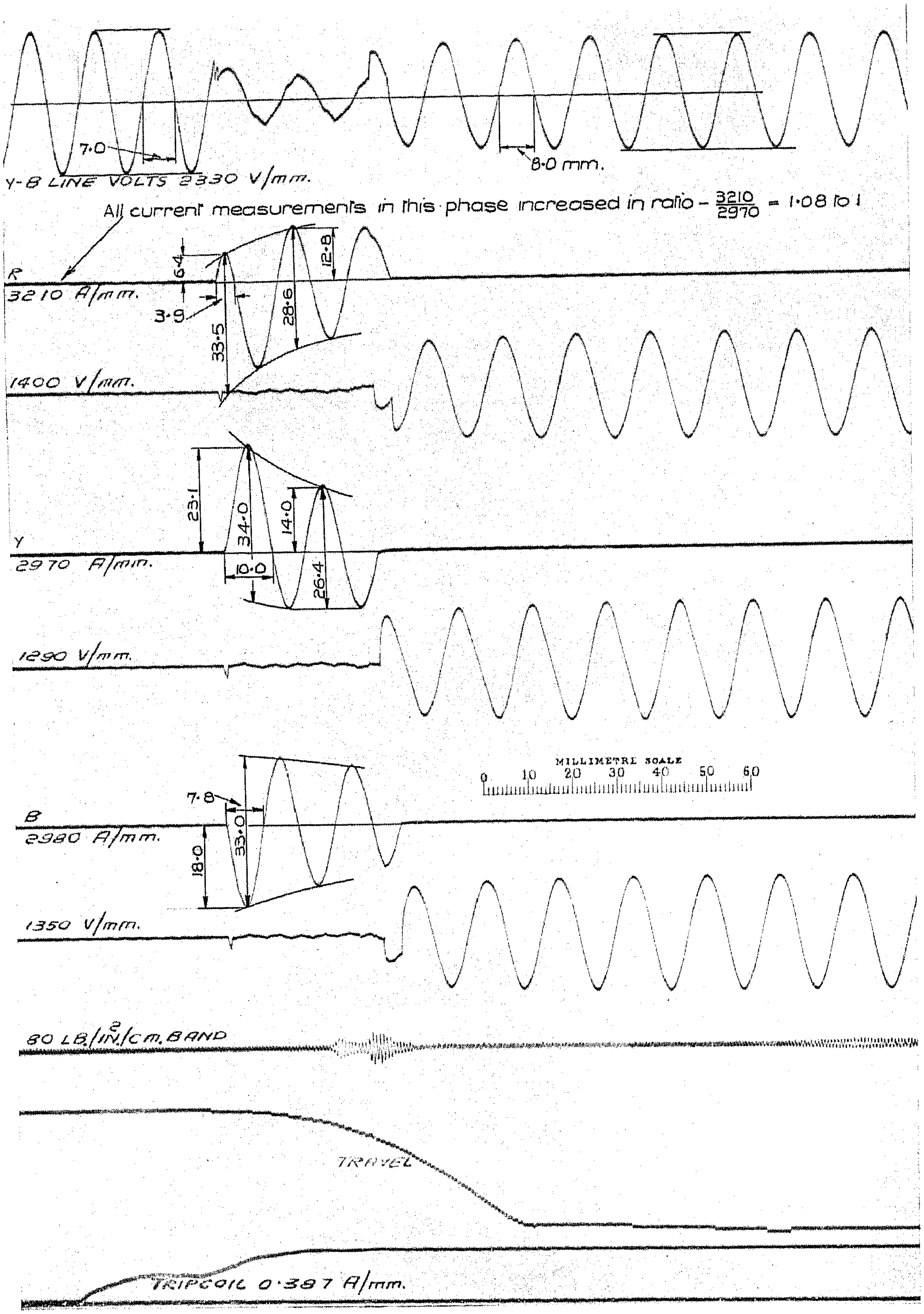

7·0
8·0 mm.
Y-B LINE VOLTS 2330 V/mm.
All current measurements in this phase increased in ratio - 3210/2970 = 1·08 to 1
R
3210 A/mm.
6·4
3·9
33·5
28·6
12·8
1400 V/mm.
23·1
34·0
14·0
Y
2970 A/mm.
10·0
26·4
1290 V/mm.
MILLIMETRE SCALE
0 10 20 30 40 50 60
7·8
B
2980 A/mm.
33·0
18·0
1350 V/mm.
80 LB./IN.²/CM. BAND
TRAVEL
TRIPCOIL 0·387 A/mm.

Fig. 4

the total current during the first half-cycle is denoted by I, and the amplitude of the alternating component, at the time this peak is reached, is denoted by I_a. Then the ratio I_a/I can be found from the curves in Fig. 1 (see Plate 1, facing page 144).

It will be seen that Fig. 1 shows a group of curves, six in all, each one of which corresponds to a certain value of a quantity κ, which is defined in the Appendix. For practical purposes κ may be taken as the power factor of the circuit diminished by 7·5 % of its value; it is, in fact, the difference between two other quantities, denoted by k and h respectively, which define the decrement-factors for the direct and alternating components. The quantity k is, to many engineers, more familiar as "tan δ," so that the power factor is $k/\sqrt{[1 + k^2]}$. The quantity h defines the decrement in the alternating component and, in the test-plant oscillograms studied by the author, it is throughout of the order of $0 \cdot 1k$. The use of an approximate value of κ, in the assumption that it is equal to the power factor less 7·5 %, will not produce an error exceeding 2·5 % in the deduced value of I_a, provided h is not less than $0 \cdot 05k$ or greater than $0 \cdot 2k$.

There are a few points which should be noted in connection with this group of curves. All the curves intersect in the point $r = 1$, $I_a/I = 1$; because, when the time-intercept is equal to one half-cycle, there is no asymmetry, and I_a is equal to I for all values of k.

For values of r less than unity, only two curves are shown, viz. those for $\kappa = 0$ and $\kappa = 0 \cdot 3$. As may be seen from Table 1, the values of I_a/I, for such values of r, vary very little with κ, so that these two curves give as much as is required for a reasonably accurate interpolation.

For values of r exceeding 1·2, curves are shown corresponding to the values 0, 0·06, 0·12, 0·18, 0·24, and 0·30 of the quantity κ. It will be seen that the curve for $\kappa = 0$ extends up to the line $r = 2$, but that the remaining curves are shown dotted for the larger values of κ. It is theoretically possible, with zero power factor and full asymmetry, for the time-intercept to have the maximum value of two half-cycles; this explains why the curve for $\kappa = 0$ extends up to the line $r = 2$. When the power factor is not zero, the value of r for a first-zero must be less than 2, and the dotted portions of the curves refer to "second-zeros." They are included because they may be of use in cases where the first-zero is too close to zero-time to be used with accuracy.

METHOD No. 2

This method is applicable only to the oscillogram of a three-phase short-circuit, and depends upon a measurement of the first peak value of the total current in each of the three phases. As in the case of the method previously described, it involves also a knowledge of the power factor of the circuit. It has the disadvantage that, if the amplitude of the alternating component is not the same in all three phases, its accuracy is liable to be affected.

To use the method it is first of all necessary to number the phases in the order in which the three peak values occur; that is to say, the phase in which the peak value is reached at the earliest time is numbered "one," and so on. This numbering having been carried out, let I_1, I_2, and I_3 denote the peak values in the three phases so numbered, and let I_a denote the alternating component at the time when the peak I_2 is reached. Then

$$I_a = I_1 + I_2 + I_3 + \frac{k\pi}{3}(I_3 - I_1)$$

It is important to note that $I_1 + I_2 + I_3$ is the ***algebraic*** sum of the three currents; I_2 is always of opposite sign to I_1 and I_3, whilst I_3 is always greater than I_1, if the numbering has been correctly carried out. If p be the power factor, $k = p/\sqrt{[1 - p^2]}$, and for low power factors k is sensibly equal to p. With high power factors the formula is liable to give slightly too high a value of I_a; by taking k equal to p for all power factors not exceeding 0·3 this liability is partially corrected.

EXAMPLES

In order that the values of I_a, given by these two methods, may be checked against values obtained by the usual method, oscillograms showing several current loops are used in these examples. The three oscillograms concerned are reproduced in Figs. 2, 3, and 4 (Plates 2, 3, and 4 respectively), and the scale measurements are shown thereon. Since the measurements were made on photostats of prints, it is possible that their accuracy has suffered in consequence; in any case they do not correspond to the scale reproduced on each oscillogram. Furthermore, in order that Method 2 should be applicable, they have been increased where necessary to correspond to the "current scale"; this also is indicated, where relevant, on each reproduced oscillogram. For example, all current measurements in the "red" phase on Fig. 2 have been increased in the ratio of 2 140 to 2 100, these figures representing the current scale (amp./mm.) for the red and yellow phases respectively.

The "zero-current" trace, and all horizontal current traces, have an appreciable width; measurements have, therefore, been taken to the lower edge of each trace; but in the case of the intercept $r\pi$ the measurement has, in all cases, been taken along the centre of the width of the zero-current trace.

There is one measurement whose accuracy presents some difficulty. This is the measurement taken from the phase-to-phase voltage trace at the top of each oscillogram, giving the scale of the half-cycle or π in millimetres. The trouble is due to the fact that the short-circuit current slows up the generator and the frequency drops. This effect is, of course, most evident in tests where the MVA is high; thus in Fig. 4, which shows an oscillogram of a 1 500-MVA test, the scale of a half-cycle is 7·0 mm. before, and 8·0 mm. after, the test. In this case, since the short-circuit lasted for 5 half-cycles, a value of 7·2 mm. has been taken, corresponding to the average value during the first full cycle.

The application of Methods 1 and 2 to each of these three oscillograms is set out in tabular form in Examples Nos. 1, 2, and 3 on page 146.

It should be noted that all current measurements are given in millimetres, scaled from the oscillograms; it is unnecessary, for the purpose of these examples, to convert the scale readings to amperes.

Example No. 1 (see Fig. 2, Plate 2)

250 MVA AT 6·6-KV; 100 % "SYMMETRICAL" TEST

	Phase	R—No. 1	Y—No. 3	B—No. 2
I_a from envelopes	$2I_a$	36·0	36·0	36·1
	I_a	18·0	18·0	18·05
Method No. 1	$r\pi$	3·65 mm.	11·7	8·35
	π	7·05 mm.	7·05	7·05
	r	0·518	1·66	1·18
	Power factor	Found to be 0·081 approx.		
	κ	Power factor less 7·5 % = 0·075		
	I_a/I	3·20	0·557	0·78
	I	+ 6·0	+ 33·0	− 22·5
	I_a	19·2	18·4	17·6
	Discrepancy	+ 6·7 %	+ 2·2 %	− 2·5 %
Method No. 2	$I_1 + I_2 + I_3$	6·0 − 22·5 + 33 = 16·5		
	k	0·081		
	$k\pi/3$	0·085		
	$I_3 - I_1$	27		
	$\frac{k\pi}{3}(I_3 - I_1)$	2·3		
	I_a	18·8		
	Discrepancy	+ 4·5 %		

Example No. 2 (see Fig. 3, Plate 3)

1 500 MVA AT 33-KV; 10 % "SYMMETRICAL" TEST

	Phase	R—No. 1	Y—No. 3	B—No. 2
I_a from envelopes	$2I_a$	30·2	30·3	32·0
	I_a	15·1	15·15	16·0
Method No. 1	$r\pi$	11·0* mm.	9·2	6·0
	π	5·7 mm.	5·7	5·7
	r	1·93*	1·61	1·05
	Power factor	Found to be approx. 0·04		
	κ	Power factor less 7·5 % = 0·037		
	I_a/I	0·61	0·555	0·927
	I	2·8/25·8*	+ 28·0	− 16·9
	I_a	15·7	15·5	15·7
	Discrepancy	+ 4·0 %	+ 2·3 %	− 2·0 %
Method No. 2	$I_1 + I_2 + I_3$	2·8 − 16·9 + 28·0 = 13·9		
	k	0·04		
	$k\pi/3$	0·042		
	$I_3 - I_1$	25·2		
	$\frac{k\pi}{3}(I_3 - I_1)$	1·06		
	I_a	14·96		
	Discrepancy	3·0 % lower than average from envelopes		

Example No. 3 (see Fig. 4, Plate 4)

1 500 MVA AT 33-KV; 100 % "SYMMETRICAL" TEST

	Phase	R—No. 1	Y—No. 3	B—No. 2
I_a from envelopes	$2I_a$	33·5	34·0	33·0
	I_a	16·75	17·0	16·5
Method No. 1	$r\pi$	3·9 mm.	10·0	7·8
	π	7·2 mm.	7·2	7·2
	r	0·54	1·39	1·08
	Power factor	Found to be 0·30 approx.		
	κ	Power factor less 7·5 % = 0·28		
	I_a/I	2·80	0·71	0·90
	I	+ 6·4	+ 23·1	− 18·0
	I_a	17·9	16·4	16·2
	Discrepancy	+ 7·2 %	− 3·7 %	− 2·0 %
Method No. 2	$I_1 + I_2 + I_3$	6·4 − 18·0 + 23·1 = 11·5		
	k	0·30 (being taken as equal to power factor)		
	$k\pi/3$	0·314		
	$I_3 - I_1$	16·7		
	$\frac{k\pi}{3}(I_3 - I_1)$	5·25		
	I_a	16·75		
	Discrepancy	Nil, compared with average from envelopes		

From these examples it will be seen that the only "discrepancies" exceeding 4 % in the use of Method 1 were in connection with small minor loops, where the value of r cannot be scaled with sufficient precision to make an accurate result probable. In the case of Example No. 3 it is likely that the values of I_a obtained by Method No. 1 are more reliable than those obtained from the envelopes; this is so because the envelopes have considerable curvature and are not very easily drawn with accuracy in the neighbourhood of the first current peak.

A COMBINATION OF METHODS 1 AND 2

It may be remarked that, even if there is no previous knowledge of the power factor, except that its value lies between 0 and 0·3, a value of I_a accurate to within about 5 % may be obtained from a three-phase "single-loop" oscillogram by a combination of Methods 1 and 2, provided interruption does not occur in any phase until the first loop in phase No. 3 has been completed.

This "combination method" relies on the fact that in phase No. 2, the value of r lies, almost invariably, between 0·8 and 1·2, and cannot be far outside these limits. For such values of r the ratio I_a/I varies very little with κ, so that, using the value $\kappa = 0·15$ in Fig. 1, a first approximation to the value of I_a may be obtained from phase No. 2. Now the formula of Method 2 gives the value of I_a when k is known, and conversely it gives a very rough value of k when I_a is known. When k is small, the value so obtained may be very wide of the mark as a percentage, but the arithmetical difference between it and the true value will probably not greatly exceed 0·06. From this approximate value of k the corresponding value of κ is obtained, and then, using Method 1, the value of I_a in all these phases can be deduced.

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* These quantities refer to the second peak and second zero in the red phase, showing use of dotted portions of curves in Fig. 1.

Using this combination of Methods 1 and 2 on the data of Example No. 1, the following result is obtained:—

r (phase No. 2) $= 1{\cdot}18$
I_a/I (from Fig. 1, using $\kappa = 0{\cdot}15$) $= 0{\cdot}80$
$I = 22{\cdot}5$
I_a (1st approximation) $= 18{\cdot}0$

Using formula of Method 2; $18{\cdot}0 = 16{\cdot}5 + \frac{k\pi}{3}27$;

$k = 0{\cdot}053$
$\kappa = 0{\cdot}053 \times 0{\cdot}925 = 0{\cdot}049$

Using this revised value of κ for a second approximation,
r (phase No. 3) $= 1{\cdot}66$
$I_a/I = 0{\cdot}55$
$I = 33$
$I_a = 18{\cdot}2$ in yellow phase (No. 3)

r (phase No. 2) $= 1{\cdot}18$
$I_a/I = 0{\cdot}785$
$I = 22{\cdot}5$
$I_a = 17{\cdot}6$ in blue phase (No. 2)

Ignoring the red phase, where a small minor loop is involved, the average value of I_a for the yellow and blue phases is 17·9, which may be compared with the average 18·02 obtained from the envelopes.

Accuracy

Provided the generated voltage is free from harmonics, the formula on which Method 1 is based, and from which the curves in Fig. 1 are derived, has an accuracy exceeding that which is likely to be attained in scaling the values of I and r from the oscillogram. In practice, therefore, this method should give results whose accuracy is dependent only on the precision with which these quantities can be scaled.

If the generated voltage contains harmonics which are not insignificant, the meaning of I_a is ambiguous, and its value, as determined from the ordinate between the envelopes of positive and negative peaks, is likely to differ from its value as given by Method 1. Any such discrepancy, which is too great to be explained by lack of precision in scaling, is probably due to this cause.

It is shown in the Appendix that the formula of Method 2 has a tendency, at high power factors, to give a value of I_a up to 5 % too high. The factors necessary to produce this maximum error will, however, seldom be present simultaneously. The inherent weakness of this method lies in the unavoidable assumption that the alternating component of the current has the same amplitude in all three phases. If this assumption is not approximately true in fact, the accuracy of the method suffers seriously, since it may not then give the average value of I_a for the three phases.

APPENDIX

Notation

E = peak value of phase volts.
t = time interval, measured from commencement of short-circuit. The unit of time is taken, for convenience, as one half-cycle divided by π.
i = instantaneous value of total current (amp.) at time t.
I = first peak value of total current, occurring at time $t = \tau$.
I_a = amplitude of alternating component at time $t = \tau$.
I_{a0} = amplitude of alternating component at time $t = 0$.
τ = time at which current reaches its first peak value.
R = resistance of circuit (ohms).
L = inductance of circuit. The unit of inductance is the henry divided by 2π times the frequency, so that L is also the reactance in ohms.
$k = R/L$ = ratio of resistance to reactance.
Z = impedance of circuit $= L\sqrt{[1 + k^2]}$.
e^{-kt} = decrement-factor for direct component (as shown by analysis).
e^{-ht} = decrement-factor for alternating component, when t is small. (This is the definition of h.)
$\kappa = k - h$
α = phase angle of voltage at time $t = 0$.
β = arc tan κ.
$r\pi$ = time at which current reaches its first zero value after commencement.
$\theta = -(\alpha + \beta)$.

In the foregoing notation, the decrement-factor for the alternating component, when t is small, is represented by e^{-ht}. This decrement-factor is, in fact, of the form

$$\frac{1 + me^{-h_1t} + ne^{-h_2t}}{1 + m + n}$$

But h_1 and h_2 are very small quantities, so that, when t is small, the exponentials can be replaced by the first two terms of their expansions. It follows that, if $h = (mh_1 + nh_2)/(1 + m + n)$, e^{-ht} can be used to represent the decrement-factor for the alternating component during the first cycle.

Analysis

The short-circuit current, at any time t after its commencement, is obtained by solving the differential equation:—

$$L\frac{di}{dt} + Ri = Ee^{-ht}\sin(t + \alpha) \quad . \quad . \quad (1.0)$$

Solving this equation by the usual method, it is found that

$$i = I_{a0}\left\{e^{-ht}\cos(t + \alpha + \beta) - e^{-kt}\cos(\alpha + \beta)\right\} \quad (1.1)$$

after replacing $-\frac{E}{Z}\left\{\frac{1 + k^2}{1 + \kappa^2}\right\}^{\frac{1}{2}}$ by I_{a0}

Method 1.

If I, the first peak value of i, and πr, the time at which the current reaches its first zero value after commencement, can be obtained from an oscillogram, then using equation (1.1) it is possible to deduce the value of I_a, provided the value of κ, or $k - h$, is known. This is done as follows.

It will be assumed that $\alpha + \beta$, or $-\theta$, has a range of values between 0 and $-\pi$, as r varies from 0 to 2. With this convention, the first peak value of i is always positive, and it occurs near the time when $t = \theta$.

Since $i = 0$ when $t = r\pi$, equation (1.1) gives

$$e^{-hr\pi} \cos (r\pi - \theta) - e^{-kr\pi} \cos \theta = 0$$

whence
$$\tan \theta = \frac{e^{-\kappa r\pi} - \cos r\pi}{\sin r\pi} \quad . \quad . \quad . \quad (1.2)$$

Again, when $t = \tau$, $i = I$, and $I_{a0}e^{-h\tau} = I_a$, so that

$$I = I_a\left\{\cos (\tau - \theta) - e^{-\kappa\tau} \cos \theta\right\} \quad . \quad . \quad (1.3)$$

Since θ can be found from equation (1.2), equation (1.3) will give the required value of I_a as soon as τ is known. Now τ is the time at which i has a maximum value, and it is not necessary to determine τ with great precision in order to find an accurate value of this maximum; a small error in τ will scarcely affect the derived maximum value of i, just because this value is a maximum. The following approximation has all the accuracy required when κ does not exceed 0·3.

Since $di/dt = 0$ when i is a maximum, differentiating equation (1.1) and putting $t = \tau$ gives

$$e^{-h\tau} \sin (\tau - \theta) = ke^{-k\tau} \cos \theta - he^{-h\tau} \cos (\tau - \theta)$$

or, since $\kappa = k - h$,

$$\sin (\tau-\theta) = \kappa e^{-\kappa\tau} \cos \theta + h\left\{e^{-\kappa\tau} \cos \theta - \cos (\tau-\theta)\right\} \quad (1.4)$$

Now h is small compared with κ, and is smaller still compared with unity, so that, as an approximation, the second term on the right of equation (1.4) can be ignored. Furthermore, if κ be not greater than 0·3, cubes and higher powers of κ can also be ignored in comparison with unity. With these approximations,

$$\begin{aligned}\cos (\tau - \theta) &= \sqrt{[1 - \sin^2 (\tau - \theta)]} \\ &= 1 - \tfrac{1}{2}\kappa^2 e^{-2\kappa\tau} \cos^2 \theta \quad . \quad . \quad (1.5)\end{aligned}$$

But equation (1.4) shows that $\tau = \theta + \kappa \cos \theta$ when terms involving squares of κ can be ignored, and the second term of (1.5) already contains the factor κ^2, so that, if κ^3 can be ignored compared with unity, (1.5) may be written

$$\cos (\tau - \theta) = 1 - \tfrac{1}{2}\kappa^2 e^{-2\kappa\theta} \cos^2 \theta \quad . \quad . \quad (1.6)$$

Again, using the expansion of $\sin (\tau - \theta)$ in powers of $(\tau - \theta)$, it is easily found from (1.4) that

$$\tau - \theta = \kappa e^{-\kappa\tau} \cos \theta + \tfrac{1}{6}\kappa^3 e^{-3\kappa\tau} \cos^3 \theta + \ldots$$

or
$$\kappa\tau = \kappa\theta + \kappa^2 e^{-\kappa\tau} \cos \theta + \ldots$$

so that, ignoring cubes of κ and higher powers,

$$e^{-\kappa\tau} = e^{-\kappa\theta}\left\{1 - \kappa^2 e^{-\kappa\tau} \cos \theta\right\}$$

and, to the same approximation,

$$e^{-\kappa\tau} \cos \theta = e^{-\kappa\theta} \cos \theta \left\{1 - \kappa^2 e^{-\kappa\theta} \cos \theta\right\} \quad (1.7)$$

Combining equations (1.3), (1.6), and (1.7), it follows that

$$I = I_a\left\{1 - e^{-\kappa\theta} \cos \theta + \tfrac{1}{2}\kappa^2 e^{-2\kappa\theta} \cos^2 \theta\right\} . \quad (1.8)$$

where
$$\tan \theta = \frac{e^{-\kappa r\pi} - \cos r\pi}{\sin r\pi} \quad . \quad . \quad . \quad (1.2)$$

Equations (1.8) and (1.2) enable the ratio I_a/I to be calculated for any given values of κ and r. This has been done for the values 0, 0·06, 0·12, 0·18, 0·24, and 0·30 of κ, and for values of r between 0·4 and 2·0. Table 2 shows the method used for these calculations in the case when $\kappa = 0{\cdot}24$, whilst Table 1 gives the full list of calculated values of I_a/I.

It may be remarked that the approximation used in equations (1.5) to (1.7) is, in fact, more accurate than appears at first sight. Equation (1.8) is still correct even if terms containing h, hk, and k^3, are not ignored in comparison with unity.

Method 2.

This method may be used to determine the value of I_a from the oscillogram of a three-phase short-circuit, on the assumption that the amplitude of the alternating component is the same in all three phases. It gives the value of I_a in phase No. 2 as defined hereunder. To use the method it is necessary to know beforehand the power factor of the circuit, and the current must have reached its first peak value in all three phases before interruption occurs in any phase.

In the following analysis it will be assumed that squares of h, hk, and fourth powers of k, can be ignored in comparison with unity. If k does not exceed 0·315, these three quantities will be of the order of 0·001, 0·01, and 0·01 respectively, or smaller.

Let i_1, i_2, and i_3 be the instantaneous values of the currents in the three phases, respectively, at any time t, and let I_1, I_2, I_3 be the corresponding first peak values, the phases being numbered in the order in which the peaks occur; that is to say phase No. 1 is the phase in which the peak is reached at the earliest time. Then from equation (1.1), writing "$-\theta$" for "$\alpha + \beta$," it is easily seen that

$$\begin{aligned}
i_1 &= I_{a0}\left\{e^{-ht} \cos \left(t - \theta + \frac{\pi}{3}\right) - e^{-kt} \cos \left(\theta - \frac{\pi}{3}\right)\right\} \\
i_2 &= I_{a0}\left\{- e^{-ht} \cos (t - \theta) + e^{-kt} \cos \theta\right\} \\
i_3 &= I_{a0}\left\{e^{-ht} \cos \left(t - \theta - \frac{\pi}{3}\right) - e^{-kt} \cos \left(\theta + \frac{\pi}{3}\right)\right\} \quad (2.1)
\end{aligned}$$

Next consider equation (1.8), and substitute $I_{a0}e^{-h\theta}$ for I_a, which is permissible if hk can be ignored compared with unity. Equation (1.8) may then be written

$$I = I_{a0}\left\{e^{-h\theta} - e^{-k\theta} \cos \theta + \eta e^{-k\theta}\right\} \quad . \quad (2.2)$$

where $\eta = \frac{1}{2}\kappa^2 e^{-\kappa\theta} \cos^2 \theta$, and is a very small quantity.

Comparing equation (2.2) with equations (2.1), it follows that

$$I_1 = I_{a0}\left\{e^{-h(\theta-\pi/3)} - e^{-k(\theta-\pi/3)}\cos\left(\theta-\frac{\pi}{3}\right)+\eta_1 e^{-k(\theta-\pi/3)}\right\}$$

$$I_2 = I_{a0}\left\{- e^{-h\theta} + e^{-k\theta}\cos\theta - \eta_2 e^{-k\theta}\right\}$$

$$I_3 = I_{a0}\left\{e^{-h(\theta+\pi/3)} - e^{-k(\theta+\pi/3)}\cos\left(\theta+\frac{\pi}{3}\right)+\eta_3 e^{-k(\theta+\pi/3)}\right\} \qquad (2.21)$$

But $\cos\left(\theta - \frac{\pi}{3}\right) - \cos\theta + \cos\left(\theta + \frac{\pi}{3}\right) = 0$

whence

$$I_1 e^{-k\pi/3} + I_2 + I_3 e^{k\pi/3} = I_{a0}\left\{e^{-h\theta}(e^{-\kappa\pi/3} - 1 + e^{\kappa\pi/3}) + e^{-k\theta}(\eta_1-\eta_2+\eta_3)\right\} \qquad (2.3)$$

Again, if I_a be the amplitude of the alternating component in phase No. 2, at the time when the peak I_2 is reached, I_a may be substituted for $I_{a0}e^{-h\theta}$; and, to the same approximation,

$$e^{-\kappa\pi/3} + e^{\kappa\pi/3} = e^{-k\pi/3} + e^{k\pi/3}$$

Hence equation (2.3) becomes

$$I_1 e^{-k\pi/3} + I_2 + I_3 e^{k\pi/3} = I_a\left\{(e^{-k\pi/3} - 1 + e^{k\pi/3}) + e^{-\kappa\theta}(\eta_1 - \eta_2 + \eta_3)\right\} \quad . \quad (2.31)$$

where

$$e^{-\kappa\theta}(\eta_1 - \eta_2 + \eta_3) = \tfrac{1}{2}\kappa^2 e^{-2\kappa\theta}\left\{e^{\kappa\pi/3}\cos^2\left(\theta - \frac{\pi}{3}\right) - \cos^2\theta + e^{-\kappa\pi/3}\cos^2\left(\theta + \frac{\pi}{3}\right)\right\}$$

and, if fourth powers of κ can be ignored, this small term is equal to

$$\tfrac{1}{2}\kappa^2 e^{-2\kappa\theta}\left\{(\tfrac{1}{2} - \cos 2\theta) + \frac{\kappa\pi}{3}\cdot\frac{\sqrt{3}}{2}\sin 2\theta\right\}$$

Now θ is close to the time at which the current in phase No. 2 reaches its first peak value, so that θ cannot be much less than $\pi/3$ or greater than $2\pi/3$. If, therefore, κ has a maximum value of 0·30, it is found that this small term varies from a little less than + 0·03, through 0·031 as a maximum, to + 0·01. Its rejection introduces a positive error into the value of I_a which, with power factor 0·3, lies between 1 % and 3 %, and which with low power factors is quite insignificant. Rejecting it, equation (2.31) becomes

$$I_1 e^{-k\pi/3} + I_2 + I_3 e^{k\pi/3} = I_a(e^{-k\pi/3} - 1 + e^{k\pi/3}) \qquad (2.32)$$

Substituting hyperbolic functions for the exponentials,

$$I_a\left(2\cosh\frac{k\pi}{3} - 1\right) = (I_3 + I_1)\cosh\frac{k\pi}{3} + (I_3 - I_1)\sinh\frac{k\pi}{3} + I_2$$

Rearranging the terms and dividing throughout by cosh $(k\pi/3)$,

$$I_a = I_1 + I_2 + I_3 + (I_3 - I_1)\tanh\frac{k\pi}{3} - (I_2 + I_a)\left(1 - \operatorname{sech}\frac{k\pi}{3}\right) \qquad (2.33)$$

Now from the second of equations (2.21), ignoring the small term,

$$(I_2 + I_a)/I_a = e^{-\kappa\theta}\cos\theta$$

and this varies from + 0·37 to − 0·27 as θ varies from $\pi/3$ to $2\pi/3$, still supposing that κ has the maximum value of 0·30. With the same supposition $\left(1 - \operatorname{sech}\frac{k\pi}{3}\right) = 0{\cdot}05$. Hence, with a power factor of 0·3, the last term in equation (2.33) has a range of values from approximately $+ 0{\cdot}02 I_a$ to $- 0{\cdot}014 I_a$. Rejecting the last term, equation (2.33) becomes

$$I_a = I_1 + I_2 + I_3 + (I_3 - I_1)\tanh\frac{k\pi}{3} \quad . \quad (2.4)$$

In deriving equation (2.4), two small terms have been rejected. When the power factor equals 0·3, the first involves a positive error, in the value of I_a, of not less than about 1·0 per cent or greater than about 3·0 per cent. The second involves an error, under the same circumstances, which varies correspondingly from about − 1·4 to + 2·0 per cent. Both errors are insignificant at low power factors. It follows that, with 0·3 power factor, the value of I_a, as given by equation (2.4), will have an error lying between − 0·4 and + 5·0 per cent.

For values of k not exceeding 0·315, tanh $(k\pi/3)$ is very nearly equal to $k\pi/3$, and for practical purposes equation (2.4) may be written

$$I_a = I_1 + I_2 + I_3 + \frac{k\pi}{3}(I_3 - I_1) \quad . \quad . \quad (2.41)$$

If p be the power factor, $k = p/\sqrt{[1 - p^2]}$; so that, for small power factors, k is sensibly equal to p. For high power factors (not exceeding 0·3) k is slightly greater than p. If, however, k be taken as equal to p for all values of p, the small correction, so introduced, tends partially to counteract the tendency of the formula to give too high a value for I_a at high power factors.

DISCUSSION ON
"PLASTICS AND ELECTRICAL INSULATION"*

TEES-SIDE SUB-CENTRE, AT MIDDLESBROUGH, 7TH DECEMBER, 1938

Dr. P. D. Ritchie: It would be interesting to learn the views of the authors on two points—one of immediate practical interest, the other with a bearing which is at present rather academic but which may have practical developments. When a pure phenol-formaldehyde resin, free from filler, is maintained at its curing temperature, the condensation process results ideally in a progressive evolution of water vapour as the material passes from its original thermoplastic form to the cross-linked thermo-hardened form. The amount eliminated approaches a theoretical limit, presumably asymptotically, so that after infinite time no more water could possibly be evolved. In practice, of course, the resin is considered to be fully cured in a finite and relatively short time. Precisely what is meant by the term "fully cured" is open to discussion, though I suggest that it indicates to most people a material which, though it may contain a small proportion of un-reacted methylol groups which would have reacted with nuclear hydrogen on more prolonged heating, will nevertheless remain permanently in this condition unless again raised to the curing temperature. But are we, in fact, justified in assuming that such a system will be permanent, even if kept well below the curing temperature? Is it not at least theoretically possible that a phenolic resin which evolves 95 % of the maximum possible amount of water after a normal curing of, say, 10 minutes at 150° C., will slowly evolve the last 5 % on keeping in service for, say, 10 years at temperatures fluctuating between room-temperature and 70° C.? I have no positive information on this point, though I have recently found slight indications that such a process may go on under certain conditions. The question is obviously of great importance in high-grade insulation work, since the power factor depends upon, amongst other things, the presence of polar groups (such as the methylol group) in the molecule, or of polar molecules (such as water) in the mass. Any change in the amount thereof may cause a slow cumulative rise in power loss: and it seems to me that more definite information on this question would be a valuable addition to our knowledge.

The next question concerns the development of power-factor maxima for certain plastics, when this quantity is plotted against temperature, over a range of frequencies. One well-known and typical case has already been discussed more than once in the *Journal*.† Here, it was shown that for a certain mixture of chlorinated diphenyls, the power loss measured at any given frequency rises to a sharp maximum at a definite temperature, and that this maximum moves along the abscissa of increasing temperature as the frequency is increased. It thus happens that at power frequencies and radio frequencies the power factor at room temperature is satisfactorily low, but rises to a higher value at the intermediate audio-frequencies. It is, then, obviously important to consider average working temperature and frequency in selecting a dielectric for any given purpose. Other cases of a similar type are known. On the other hand, however, the majority of the better-known plastics, such as the phenolic, urea, and acrylic resins, show merely a progressive rise of power factor with temperature, with no sign of a maximum. To quote one example, the power factor of a commercial poly-methyl methacrylate (at 800 cycles per sec.) rose smoothly from about 6 % at 15° C. to about 28 % at 75° C. Is it, then, to be assumed that there is some fundamental difference between these two types of curve—the latter, showing no maximum, and corresponding to materials with large complex chain- or mesh-molecules; and the former, corresponding to smaller and simpler molecules, where there is a maximum power-loss between two minima, at one of which, on Debye's theory, orientation of the polar molecules is totally inhibited by high "apparent internal viscosity," whereas at the other this rather vaguely-defined parameter is so reduced by the temperature-rise that practically free orientation is possible? Or is it more likely that all the curves are of the same type, but that to realize a maximum for the more complex plastics it would be necessary to follow the curve further into the extremes of temperature?

Two points in connection with specific plastics may be of interest in conclusion. Dr. Caress has mentioned that he is inclined to look for the greatest electrical progress in the thermoplastic rather than in the thermo-hardening materials, especially on the grounds that the former are more likely to display toughness and absence of brittleness. It is, however, worthy of note that one of the more recent thermoplastics, poly-N-vinyl-carbazole, while displaying very good dielectric properties and a remarkably high softening-point, is nevertheless of a curiously brittle, flaky, and almost fibrous consistency when moulded. The other point is that although the authors state that the aniline-formaldehyde resins are non-tracking, the only specimen I have been able to examine was quite readily tracked very badly.

Mr. G. W. Nicholls: The general object of the authors in preparing their paper has been to discuss the properties which the electrical engineer considers necessary for a particular dielectric for any one specific purpose, and what the chemist is able to supply to meet his requirements; in other words, the relation between the molecular structure and the electrical properties of a plastic, with particular reference to power factor and permittivity. The authors have very clearly illustrated and explained by models and chemical formulae the structure of the various plastics, and it seems that a possible solution of the problem of finding the dielectric with the required electrical and mechanical properties mentioned is to concentrate on a product with a molecular structure intermediate between that of a straight-chain product and a cross-linked product.

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* Paper by Dr. L. HARTSHORN and Messrs. N. J. L. MEGSON and E. RUSHTON see vol. 83, p. 474).

† See, for example, W. JACKSON: *Journal I.E.E.*, 1936, vol. 79, p. 572, Fig. 4.

Unfortunately one of the biggest disadvantages of the thermo-plastic materials, so far as high-voltage work is concerned, is their low softening-point, and as quite a number of mouldings used at high voltages may have to withstand a temperature of approximately 80° C. without showing any sign of deformation it will be seen that the use of thermoplastics with softening temperatures varying from 40° C. to 70° C. is limited in this direction.

Amongst the softening-point values quoted in Table 2 the value for cellulose acetate is given as 60° C., but the value quoted by Mr. A. R. Dunton and Dr. A. Caress* was 45° C. (Martens test). Is this difference due to the method of test adopted, or to varying amounts of plasticizers used?

Softening-temperature tests, which differ for each testing authority (such as British Electrical and Allied Industries Research Association, Verband Deutscher Elektrotechniker, and American Society for Testing Materials), ought to be brought more in line with one another so that the values quoted in literature, as far as the electrical engineer is concerned, are comparable. Usually, and particularly for urea-plastics, they are much in excess of what is regarded as the maximum safe operating temperatures.

Hence softening temperature, so far as urea plastics are concerned, is no indication of the maximum safe working temperature, and I am of the opinion that the 100° C. quoted by the authors as the maximum temperature is excessive, particularly if the air is dry.

There exists generally among chemists and engineers to-day great difference of opinion on the method of obtaining comparative values of softening temperatures of plastics, and it may be advisable to have a separate method of test for thermosetting and thermoplastic materials, inasmuch as the softening point of the latter appears to be of little significance when it is considered that some of them may flow when loaded even under ordinary atmospheric conditions.

I notice that the authors distinguish thermoplastic materials from thermosetting materials by means of their softening temperatures, referring to one as the softening temperature and to the other as the maximum temperature, which I assume is the maximum safe working temperature. Had they the same idea in mind when classifying these materials in two groups, i.e. softening temperature and maximum temperature?

[The authors' reply to this discussion will be found on page 154.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 9TH JANUARY, 1939

Dr. P. D. Ritchie: Of the many possible lines of research indicated by the authors one of the most promising lies in the co-polymerization of two different polymerizable materials—that is to say, in the production of large chain- or cross-linked molecules whose component units are not all alike. The authors touch briefly upon this in their reference to Staudinger's already classical work on the co-polymerization of styrene and divinyl benzene. It is satisfactory to note that this has been recently extended in this country by Norrish and Brookman, who have given examples of the profound modification in physical properties brought about by cross-linking styrene, methyl methacrylate, and vinyl acetate, by a series of different divinyl compounds. Other similar cases of co-polymerization are becoming increasingly frequent. The valuable properties of certain of the plastics known by the trade names Mipolam and Vinylite, for example, are attained by co-polymerizing vinyl acetate and vinyl chloride, which individually give well-known polymers, though here there is no cross-linking but merely a rather random alternation of the two different groupings along each chain. Further, to leave for the moment the field of electrical insulation, the oil-resisting rubber-like Buna plastics which have emanated from Germany in the past few years are made by co-polymerizing butadiene, which is itself closely akin to the unit grouping of natural rubber, along with other modifying materials. Buna "S," for example, is made by utilizing styrene as the co-polymer, and Perbunan by using acrylic nitrile: and in this way, by judicious choice of co-polymers, new and valuable oil-resisting properties have been superimposed on the rubber-like properties of pure polymerized butadiene. Very recently too, new plastics have been described in America, made in an unusual way by polymerizing indene, which by itself gives a thermoplastic polymer similar to polystyrene, along with phenol, thus inducing the property of compatibility with cellulose plastics and opening up new possibilities in the paint and varnish industry. Many cases come to mind where the properties of two thermoplastics could with advantage be combined if a suitable co-polymerization could be effected. For example, the German thermoplastic Luvican has an unusually high softening point, but a rather brittle and flaky structure: whereas polyvinyl chloride has a tough and flexible consistency, but a low softening-point. By co-polymerizing the two corresponding monomers, a very valuable plastic might be obtained. Unfortunately, there is as yet no certain way of combining the good properties while suppressing the bad; nor can all theoretically possible co-polymerizations be effected technically. But there is obviously a wide field here for chemical and electrotechnical research; and it is significant to note that, in the above-mentioned work of Norrish and Brookman, it was found possible to correlate to some extent the properties of the final cross-linked plastic and the nature of the cross-linking compound, thus foreshadowing the systematic building-up of polymers conforming to a previously-decided specification.

The authors seem to have shed some light on a somewhat vexed question, namely the effect of residual uncombined phenol in laminated insulating materials of the paper-cum-phenolic resin type, commonly known by that wholly regrettable but well-established term "bakelized paper." It seems to be accepted nowadays as axiomatic that such free phenol must be reduced to the absolute minimum. It has never been quite clear to me that there was any experimental or statistical evidence to support this contention, though it is certainly reasonable to assume on theoretical grounds that strongly polar molecules like those of phenol will have an adverse effect on power factor. Phenol has a dipole moment only slightly lower than that of water itself, whose presence in a dielectric is universally accepted as being highly deleterious. It is therefore striking to find that the authors observed only a negligible effect upon the power factor of phenolic-resin films when an intentional addition of 2·5 % of phenol was made. If we may assume that this free phenol was still actually present after stoving, it will be seen that a laminated insulator containing 35 % of this phenolic resin as a binder would have an average free phenol content of about 0·8 %—a figure which, according to normally accepted views, would probably be regarded with a good deal of suspicion.

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* *Journal I.E.E.*, 1936, vol. 79, p. 463.

Here, then, we have a certain confusion of evidence, which is not resolved when we consider the free-phenol content of a series of commercially available laminated insulators of this type, in relation to their dielectric properties. I have had an opportunity to consider a series of such figures, and it appears that a high free-phenol content is by no means necessarily accompanied by a high power-factor, although this is admittedly sometimes the case. These facts are brought forward, not with a view to discrediting current opinion on the matter, but rather to suggesting that the rumour, if rumour it be, should be either eliminated or fully substantiated by further work on the free-phenol question.

In conclusion, a word may be said on the new textiles, woven from glass fibres, which have recently appeared on the market. Glass, of course, is in virtue of its physical properties an almost perfect example of a thermoplastic: but it has perhaps been a little difficult to reconcile this brittle, fragile medium with the usual mental images suggested by the word "plastic." Now, however, the silky and astonishingly flexible fibres of the new material present glass in a form which makes it much more readily accepted as a member of the plastics family, and a member with an extremely promising future.

Mr. G. H. Hickling: In the great majority of applications of plastics as insulating materials, mechanical properties are of first importance. This is undoubtedly true of the enormous variety of low-voltage electrical appliances which are now manufactured of moulded bakelite.

In high-voltage work, where the dielectric properties of insulating materials become of predominant importance, pure plastics have as yet found few, if any, applications. They are, however, made use of extensively for the impregnation of other non-plastic insulators such as paper and mica.

Mica alone is of little use for high-voltage insulation, owing to its poor mechanical properties and to the necessity for building it up from relatively small pieces: it is therefore used in conjunction with a suitable plastic (or "sticker") as micanite. Mica, besides possessing a high electric strength and excellent thermal properties, has the added advantage of an extremely low power-factor. If, however, it is made up as micanite with an unsuitable high-loss varnish, this property is lost, and in consequence rapid heating occurs under a high electric stress, resulting in breakdown due to thermal instability.

It will be seen, therefore, that whilst the electric strength of the varnish in micanite need not be very high—only sufficient to prevent tracking between the mica flakes—its power factor is of first importance. Now that plastics such as polystyrene, having power factors as low as 0·0004 combined with excellent electric strength, are becoming available, therefore (though this particular material appears unfortunately to suffer from a rather low softening temperature), we may anticipate a very great improvement in the composite insulating materials of which micanite and bakelized paper are the most important representatives. Possibly, too, the application of moulded products to high-voltage work may be an important field of development in the near future.

Mr. W. A. Cook: Phenol-formaldehyde laminated products under the name "bakelized paper" are well known to the transformer and switchgear designer, and have become of great importance. The designers and the users of bakelized-paper insulators are, however, continually faced with the problem of sacrificing some of the properties for the sake of others. It is possible to make grades of bakelized paper having extremely good mechanical properties and extremely high resistance to moisture; it is also possible to make grades which have excellent electrical properties; but it is extremely difficult to make a single grade which combines the maximum electrical properties with the maximum mechanical and moisture-resisting properties. One is forced, therefore, for any particular purpose, to choose between, on the one hand, a highly impregnated material with good mechanical strength and moisture resistance, and, on the other, a lightly impregnated material of high electric strength; or perhaps some grade of material which is a compromise between these two extremes. This is necessitated by the relatively poor electrical properties and high power-factor which accompany a high degree of impregnation of the paper by the resin.

Whilst the user of bakelized paper need not be unduly concerned with the actual value of the power factor, a high power-factor does increase the difficulty of dissipating the losses produced in the material, and therefore reduces the voltages and the temperature at which a particular insulator may be used.

For this reason, I believe that the main interest of the present paper to the switchgear and transformer engineer lies in the reference to such low-power-factor resins as polystyrene. Laminated paper made from polystyrene has electrical properties which are considerably better than those of the best electrical grade of bakelized paper; it has both higher breakdown values and a lower power-factor, and whereas bakelized paper shows a considerable increase in power factor with increased temperature, with a polystyrene resin the power factor does not vary appreciably with temperature. The main point of advantage is, however, that the material which has these exceptional electrical properties can at the same time have high moisture-resisting properties, approaching those of the grade of bakelized paper which is best in this respect. The use of a resin such as polystyrene therefore promises to solve the dilemma of the designer, and provide him with a material which will combine superior electrical, moisture-resisting, and other properties in one and the same material.

Also, the improved electrical power factors and electric strength will, I hope, result in reduced dimensions for insulators; and that of course is an advantage, not only from the point of view of the insulator itself but from the point of view of economy in the size of the apparatus in which it is used. The one drawback of polystyrene products—the fact that the resin softens with heat—need not be so serious a matter as might be supposed. Although it is customary to regard 90° C. and 80° C. as the maximum temperatures for transformers and switchgear respectively, such temperatures as a rule can only be obtained on part of the conductor system, and are extremely unlikely on any part of the insulator itself. So that the temperature at which the insulators have to operate will be considerably less than 90° C., and at that temperature polystyrene products are still quite hard. Moreover, softening, when it occurs, is only partial, and free fluid flow never takes place. We therefore have reason to hope that polystyrene laminated products will become of great interest to switchgear and transformer engineers.

Mr. M. Waters: It is interesting to note that the percentage moisture absorption of phenolic resins given in Fig. 4 does not appear to reach a limiting value with time, as would be expected, but appears to increase indefinitely at a slow rate. If this increase really occurs it would seem that such resins will slowly deteriorate in moist air, and after several years may lose their insulating properties. Alternatively, it is possible that the curves in Fig. 4 would have reached true limiting values if the tests had been continued for a further 5–6 months. I should be pleased to know the authors' opinion as to whether the absorption reaches a limiting value, and whether moisture will have no further effect on the electrical properties of these resins after equilibrium has been reached.

Mr. C. G. Giles: I agree with the authors on the desirability of producing resins which are impermeable to water. It is known that composite materials made with resin-base varnishes have high power-factors, which increase rapidly with temperature. I should therefore appreciate the authors' explanation of the general decrease in power factor with rising temperature shown in Fig. 5; and especially of why the power factor changes so little with temperature.

Mr. G. H. Gardner: I have felt for some time that in considering future major improvement in the quality and performance of bushings made from synthetic-resin varnish-paper one must look for some resin other than the phenol or cresol-formaldehyde type.

My company, after a considerable amount of research work, has recently been able to produce a bushing made from paper impregnated with a polystyrene resin. This new bushing is not yet fully developed, but tests show that its electric strength is at least 3 times that of bushings made from normal present-day materials, and its losses are abnormally low. It also has very good moisture-resisting properties.

Mr. R. W. Mann: The characteristics dealt with in the paper are those largely involved in high-voltage work. It is almost certain that the requirements of low-voltage plastics are very much in excess of those of high-voltage plastics from the quantity point of view. There are, broadly, two main characteristics of low-voltage plastics, which unfortunately do not seem to go hand in hand. The plastic must first of all be mechanically strong; and secondly, while its electrical characteristics in the first place are not required to be high, it must be such that having once been burnt by an arc it remains an insulator. Consideration might well be given to the gases which are given off when such low-voltage plastics burn, as such gases, if confined to the apparatus containing the plastics, are likely to give rise to serious explosions should they become ignited.

The paper also deals in detail with the relative characteristics of various new kinds of plastics, but from a technical point of view only; and it is to be hoped that the authors may at some time later have an opportunity of repeating this portion of their paper with suitable comparisons as to the commercial costs of these new plastics.

Prof. J. C. Prescott: Fig. 5 is particularly interesting if compared with the results which were obtained by B. J. O'Kane in Liverpool in 1935.* His power-factor curves, for waxes when subjected to alternating fields of high frequency (6–12 Mc./sec.), are similar in shape to the 1 000-cycle and 4 000-cycle curves for damp phenolic resins shown in this Figure. Over the range of temperatures at which these resins were tested, I assume that there was no change in physical state and that the material was a solid throughout. In the tests carried out by O'Kane the temperature range included the melting point of the wax, and the power factor with pure waxes appeared to reach a maximum in the region of the melting point. I should therefore like to ask the authors whether any figures are available for these phenolic resins in the fluid state, and whether a similar increase is manifested between the liquid and solid conditions.

On page 485 (vol. 83) the authors suggest that the transparent plastics might be used as windows for electrical instruments. I think that care would have to be exercised if these were applied to electrostatic instruments, since I remember that a sample that was shown to me some time ago exhibited very considerable electrostatic charges when rubbed lightly with a duster.

Mr. W. J. Brown: The authors have made a careful research into the properties of pure resin films; it is rarely that synthetic resins are used alone, and in most electrical applications the addition of fillers is found necessary to confer mechanical strength and other desirable properties. It would be a welcome extension of the authors' work if similar investigations were made on materials as used commercially.

A very important application of synthetic-resin composites is the manufacture of high-voltage insulation, laminated from synthetic resin and paper. Such composite materials have rendered possible the development of metalclad switchgear for high voltages; and many thousands of insulators, condenser bushings, and the like are giving excellent service—some under difficult conditions. Service conditions are made more onerous by the presence of moisture, and I believe that one of the principal causes of deterioration in insulation of the type under discussion is moisture absorption. Insulation engineers take great pains to render the materials they manufacture as water-resisting as possible, and in this connection the authors' experiments on absorption are of considerable interest. Superficially the values of 3 % to 4 % obtained on test films conditioned in an atmosphere of 75 % relative humidity appear to be high. Tests on composites containing fibrous fillers actually give much lower values. The apparent anomaly is caused by differences in the methods of reporting the amount of water absorbed. The authors express the absorption as a proportion of the volume of the resin, and their sample has a low volume and a very large surface area. Most commercial tests express absorption as a percentage of the sample weight (e.g. B.S.S. No. 316—1929). Unless particulars of the physical dimensions of the test sample are supplied it is impossible to compare the water absorption of different materials when the values are expressed as a percentage either of volume or of weight. The amount of water absorbed depends to a very large degree upon the surface area exposed, to a lesser degree upon the volume of the sample, and not at all upon the weight. There is need for a method of expressing water absorption in a way which really has meaning, so that the values obtained are an attribute of the material and not of the sample size and shape. I should be grateful if the authors would quote the water absorption of their films expressed in milligrammes of absorbed water per cm^2 of exposed surface area; a useful comparison between the films and resin composites might thus be obtained.

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* *Philosophical Magazine*, 1936, vol. 21, p. 369.

The authors' experiments on the effects of varying catalysts are interesting but inconclusive, and the investigation might be pursued by extending the work to include tests on the mechanical strength of resins manufactured with different catalysts. It is known that if two phenol-aldehyde resins are produced, one caustic soda catalysed and one ammonia catalysed, the first resin will be characterized by increased mechanical strength and increased power factor by comparison with the second resin.

The electrical properties of a laminated synthetic-resin composite do not depend entirely upon the electrical characteristics of the resin used in its manufacture; certain physical properties are of great importance. It is customary to apply resins of the phenol or cresol type in the form of alcoholic solutions, and the viscosity and surface tensions of these varnishes influence the dielectric properties of the resulting composite. One phenolic resin when coated on paper may lie entirely on the surface, while a second resin may have greater penetrating properties and fully impregnate the paper web. The product of the first resin will have a laminated structure consisting of layers of paper interleaved by layers of resin. The second will give a highly homogeneous structure without definite laminations. The difference in the dielectric properties of these two materials is marked.

The presence of water in the alcohol used for making synthetic-resin varnishes apparently has no deleterious effect on the resulting dielectric; presumably the water is removed when the solvent is evaporated. The amount of water liberated by the resin during polymerization is, however, of considerable importance, and when this is reduced by even 1 % a definite improvement in power factor results, and in particular the temperature coefficient of the composite insulation material is diminished. This improvement is effected despite the fact that 1 % decrease in the water content of the resin is a minute quantity compared with the amount of water contained in the alcohol with which it is mixed.

The information given in the paper on the properties of polystyrene resin is of great interest. This resin can now be laminated with a paper web, and despite the fact that polystyrene is a thermoplastic resin, condenser bushings are being made from this new composite material which are quite stable at 90° C. Polystyrene composite materials possess very attractive features, and much more will undoubtedly be heard of this development.

THE AUTHORS' REPLY TO THE DISCUSSIONS AT MIDDLESBROUGH AND NEWCASTLE

Dr. L. Hartshorn, and **Messrs. N. J. L. Megson** and **E. Rushton** (*in reply*): With regard to the possibility of continual changes taking place in a phenolic-resin moulding, raised by Dr. Ritchie, it seems likely that the residual methylol groups remaining in the structure will bring about such an effect. Whether the power factor will be adversely affected by such changes will depend upon the relation existing between the rates of formation of water through chemical reaction, and the rate of loss of this water from the moulding. Both these factors would be favoured by rise of temperature, but the shape and composition (e.g. nature of filler) of the moulding will also affect the rate of loss.

With regard to the remarks of Dr. Ritchie and Prof. Prescott on the power-factor maxima observed for certain plastics, we do not consider that only those materials containing relatively small and simple molecules show this effect, and that materials with more complex molecules do not. Both large and small molecules may be polar, and therefore rotate in an electric field. The chief difference between the two from our point of view is the different time of relaxation of the two systems of molecules (the time required by the molecules to resume their normal random distribution after any disturbance). A maximum value of power factor occurs when the periodic time of the applied voltage is of the same order as this time of relaxation. One can well understand that, other things being equal, a large complex molecule would have a very much longer time of relaxation than a small one, and therefore would tend to show a power-factor maximum at a very much lower frequency. The fact that maxima have been observed in one case and not in the other merely suggests that the time of relaxation in the other case is of a different order. The time of relaxation will obviously be controlled by any frictional or viscous force which opposes the rotation of the molecules, and these forces usually vary considerably with temperature. It is quite probable that, if measurements were made at very different temperatures or frequencies, maxima would be observed for the large molecules and not for the small ones.

We are interested in the comments on poly-N-vinylcarbazole, the good dielectric properties of which may be associated with the fact that only a tertiary nitrogen group is involved, which would possibly have a low polar effect. Our comments on the non-tracking properties of aniline-formaldehyde resins are not the result of personal experience but only an account of recorded information, and we are glad to have Dr. Ritchie's own observations on this point.

We agree that important developments in plastics may be anticipated from an extension of co-polymerization of different materials. Already much has been achieved in this field, and we note with interest the modification of indene with phenol to give new products, although these are more the result of chemical interaction than of strict co-polymerization.

The vexed question of the effect of free phenol on electrical properties is, unfortunately, not completely settled by our work. We believe that the phenol added to the resin is not present after stoving, because it probably combines with available methylol groups to form part of the resin structure. Only by the addition of quantities of phenol exceeding those which could combine with such groups, will it be possible to decide on the influence of the substance in the final resin.

In reply to Mr. Nicholls, the softening of a typical plastic is so complex a physical process that we do not think that a precise definition of softening point is possible. The various empirical tests that are used involve arbitrary definitions which are known to give inconsistent results in some cases. Nevertheless, the information obtained, although defective, is better than none at all, and we have therefore quoted values as a rough guide. They must be regarded as subject to considerable uncertainty. We have merely used the term "maximum temperature" to cover those cases in which the material loses its useful properties by some other process than that of mere softening, e.g. by decomposition. The discrepancies noted are no greater than could be accounted for by varying amounts of plasticizer, but we would emphasize the fact that we do not regard the terms "softening temperature" and "maximum temperature" as having a very precise meaning. The values given are those which appeared to occur most frequently in published literature, and which therefore presumably represent general experience as far as it is possible to do so.

We are interested in Mr. Cook's statement that resin-paper composites with high resin content have high power-factors and generally poor electrical properties. When we consider that the power factor of the resin is much less affected by the absorption of water than is the power factor of paper, it would appear that to obtain the best electrical properties it would be advisable to include as much resin and as little paper as possible in composite materials. That this is not the case in practice may be due to the fact that the resin is not completely cured, in which event the power factor of the composite material will, of course, increase with increasing resin content.

In reply to Mr. Waters, we cannot help thinking that equilibrium with atmospheric moisture and therefore a limiting value for water absorption would ultimately be reached, but it is impossible from our experiments to predict the time required. It must be remembered, however, that small increases of water absorption of this order have little effect on the power factor, and we do not therefore think that there would be any serious deterioration of electrical properties.

We would refer Mr. Giles to our reply to Mr. Messent in the discussion before The Institution (vol. 83, p. 469) for our explanation of the decrease in power factor with increasing temperature. It must be pointed out in connection with composite materials containing resin and filler that, although the power factor of the resin changes little with increasing temperature, the power factor of the filler usually increases considerably owing to normal ionic conduction, with the result that the power factor of the material as a whole increases with temperature.

Table B

WATER ABSORPTION OF RESIN FILMS, EXPRESSED IN MG. PER CM.^{2} OF SURFACE AREA

Sample No.	Thickness	Total surface area	Time at 75 % relative humidity	Increase in weight	Absorption
	mils	cm.^{2}	days	mg.	mg. per cm.^{2}
1	2·0	440	206	59·2	0·14
2	2·5*	445	206	67·3	0·15
3	4·8	419	206	101·9	0·24
4	6·5	86·4	206	28·0	0·32
5	2·1	445	206	41·6	0·09
6	27·0	127	219	117·8	0·93

* The thickness of this film is incorrectly given as 2·8 mils in Fig. 4 of the paper.

We agree with Mr. Mann that the risk of explosions due to gases such as hydrogen and methane which may be given off when plastic materials burn, is one which should be borne in mind in certain applications of these materials.

In reply to Prof. Prescott, we would state that, although values for phenolic resins in the fluid state are not yet available, we are investigating this matter and hope to present results in a future paper.

The electrification of windows is always apt to give trouble in very sensitive instruments, even when glass is used. A plastic of very low conductivity would obviously be quite unsuitable for this purpose, but by using one of a non-electrical grade or by deliberately adding a plasticizer of high conductivity, one might hope to improve on glass in this respect.

As requested by Mr. Brown, we have recalculated our figures for water absorption on the basis of milligrammes per cm^2 of surface area, and obtained the results shown in Table B, for the samples referred to in Fig. 4 of the paper.

The results indicate that the amount of water absorbed is not wholly dependent on the surface area, otherwise the absorption in mg. per cm^2 would be constant for all the specimens. The fact that the absorption in mg. per cm^2 increases with increasing thickness of specimen confirms our suggestion that the water absorbed does not lie on the surface but permeates the whole body of the material. The whole question of comparisons of water absorption is obviously very complex. The initial rate of water absorption must be proportional to the surface area, and the final equilibrium amount is probably proportional to the volume of the specimen. Unless information on both these points is available, any comparisons of water absorption based on tests over an arbitrary period of time are liable to be misleading.

The practical significance of Mr. Brown's remarks on the manufacture of boards with resins of different viscosities is very interesting. The difference in properties of the resulting laminated board, according to whether surface coating or full impregnation is achieved, is, however, not fundamental to the resin, but to the method of using it. So far our work has not extended to this point.

The reason why, in a varnish made up of resin in alcohol, the water in the alcohol is not deleterious, while that given off by the resin is harmful, probably lies in the fact that most of the volatile solvent is removed by warming or evaporation before hardening. The water from the resin does not of course become significant until stoving is begun.

With regard to the effect of various catalysts, we would point out that although we did not examine resins made with caustic soda as catalyst, we did show that the addition of caustic soda to a resin caused an increase of power factor, which suggests that the increased power factor mentioned by Mr. Brown may not arise from the catalytic action of the caustic soda, but from its presence as an impurity.

THE LIMITS OF THEORY IN ELECTRICAL MACHINE DESIGN*

By G. H. RAWCLIFFE, M.A., Associate Member.†

[Abstract *of Paper read before the* Mersey and North Wales (Liverpool) Students' Section, *15th March*, 1938.]

(1) INTRODUCTION

A period in an industrial design office made the author realize how wide were the discrepancies between the theory and performance of electrical machinery, and how many points of vital commercial and practical importance defied satisfactory theoretical treatment. Some of these points have been selected to illustrate why and how theory is sometimes insufficient. In a short abstract it has been necessary simply to show the nature of the problems, and to omit results of particular problems given in the original paper.

The number of variables in an electrical machine is very large, and before calculation can profitably be commenced a selection must be made of the predominant factors. It is in the making of this selection, rather than in subsequent deduction, that the real difficulty of a problem commonly lies. The examples given in textbooks are, in fact, ready-made selections of the leading factors in electrical design, and the answers give the behaviour not of actual machines but of idealized machines subject only to these selected effects. The errors correspond to the errors in the initial assumptions, and many discrepancies of performance arise from hidden assumptions in calculation.

In general it may be said that departures from calculated performance arise, theoretically, from simplification in calculating a major effect, or from ignoring a minor effect, and, practically, from manufacturing tolerances on theoretical dimensions. One very important cause of discrepancy is the tacit assumption that a sinusoidal function in space or time is a true representation of every alternating quantity involved in the calculation. This assumption is made since the sine wave is the only periodic function whose differential coefficients are of the same shape as the original function, but it is often far from true.

(2) D.C. MACHINES

(a) Commutation

The problem in d.c. machines which is theoretically most troublesome is commutation. According to the classic theory the interpole windings are designed to nullify the armature ampere-turns and to neutralize the self-induced e.m.f. in the armature coils undergoing commutation. The inductance of the coils is, however, variable and uncertain, so that no precise estimate can be made of the requisite gap flux and interpole turns; the correct value can only be fixed by test. Some of the interpole turns may better be applied as a compensating winding fitted to the main pole-tips and enclosing the armature, the magnetic axis of compensating and interpole windings being the same. The compensating winding "compensates" that part of the armature flux which completes its circuit through the main poles; the interpoles deal with the rest, and also supply the flux to oppose the armature self-induction. Interpoles and compensating windings thus divide two functions between them, and within fairly wide limits one can be strengthened by weakening the other. The ideal division of ampere-turns can, however, only be found by test, and it will vary with differing gap lengths and pole-tip shapes.

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* The original paper, of which this is an abstract, was awarded a Students' Premium by the Council.

† Liverpool University.

The classic theory takes no adequate account of brush material or size, commutator speed, current density, and the like. " Get the field form correct," so, in effect, runs the theory, " and the current may be drawn off from any brush you may care to fit on the neutral axis." A correct field form is a necessary but not a sufficient condition for good commutation, and the further quantities of brush current-density, etc., are settled only by experience, the aim being to use the smallest possible brushes and commutator. It is impossible to forecast from theory to what limiting density the present brush densities of 60–75 amp./sq. in. might be increased.

Basic theory assumes a uniform current distribution round the periphery of the armature, but in fact the current is contained in small " packets " in slots, and much variation in commutation is produced by different slottings and by lamination of the conductors.

(b) Compounding of D.C. Machines

An example of classic theory being reversed in practice is furnished by compound-wound d.c. motors. In many textbooks and among many practising engineers the idea still lingers that differential compounding is used to secure a level speed characteristic. Actually, owing to high flux densities and high armature loading, the armature magnetic field, in spite of interpoles, causes not merely distortion but reduction in flux, and many plain shunt motors would have a rising and unstable speed/load characteristic. It is usual, therefore, to fit either a compensating winding, which neutralizes the armature more effectively than interpoles, or a light *cumulative* compound winding, often known as a series stability winding. Where heavy peak loads are expected a heavier compounding is fitted, to give a normal compound-wound motor.

Differential compounding is only rarely used when, as in balancer sets, the same machine has to work either as a motor or as a generator, without alteration of the connections. Two machines coupled together may be stable even with the motor differentially compounded. It should be emphasized that the behaviour of generators is not the reverse of that of motors, since generator fields are also weakened by the saturating effect of armature reaction, which is independent of the direction of armature current-flow. Hence generators are also cumulatively compounded for level voltage characteristics, but more strongly so than armature drop alone would require.

(3) EDDY-CURRENT AND STRAY LOAD LOSSES

(a) D.C. Machines

A serious but incalculable loss in d.c. machines is that due to eddy currents in the conductors, generated during their movement through the regions of non-uniform flux distribution at the tips of the poles. This loss is reduced by lamination of the conductors, and it is customary to laminate until the reduction of cross-section is 15 %. The reduction of eddies by further lamination would not outbalance the increase in resistance.

(b) Squirrel-cage Machines

To avoid the crawling of squirrel-cage rotors, the bars are skewed one stator slot-pitch. The skewing of bare bars led to increased rotor heating and they are now usually insulated. The increased rotor heating arose from the connection through a good conductor of different parts of the rotor iron not in the same part of the stator field-form. This eased the path of the " average " eddy current, and surprisingly large reductions of heating have been obtained through insulating the rotor bars.

These examples of extra eddy-current loss differ in that the first can be measured approximately on no load, but the second varies with load and cannot be measured: both defy calculation on any but an experimental basis. Stray load losses could only be measured by tests of the highest precision, measuring both input and output exactly. Hence the recognized method of estimating efficiency is " the summation of measurable losses," and an allowance is made for stray load losses.* Their real importance lies not so much in the decreased efficiency as in the increased heating, and consequent reduced rating, which they cause. A loss of efficiency of 1 % may be tolerable, when the heating caused by this loss is not.

(4) THE IRON CIRCUIT OF A.C. OR D.C. MACHINES

(a) No-load Iron Losses

Calculations are based on eddy and hysteresis losses in standard test pieces, but the magnetic condition of the iron is much altered by punching, the alteration depending on the ratio punched-area/punched-periphery, the condition of the punching tool, the mechanical state of the iron, the speed of punching, and so on. Tests can be made with particular specimens, but the variations of the conditions of punching cannot in practice be controlled. Further, the laminations are short-circuited at the edges by burrs and by the machine frame; this causes extra eddies. There are also iron losses due to pulsation at tooth frequency. There is a time pulsation in reluctance and flux as the teeth change their relative positions, and a space pulsation of the flux, due to changes in the geometry (as distinct from the reluctance) of the magnetic circuit. Theory shows that suitable slottings and a longer air-gap will reduce these losses, but the magnitude of the change can only be roughly estimated. In the result, the iron loss is two or three times that calculated for eddy and hysteresis at fundamental frequency in the unpunched iron, and it is estimated largely from empirical data.

(b) Magnetizing Currents

Here manufacturing discrepancies quite obscure any attempt at theoretical refinement. A large part of the magnetomotive force is used on the air-gap, and 0·001 in. error in stator bore and rotor diameter, in opposite directions, may be equivalent to 10 % error in air-gap length.

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* See Reference (1).

(5) LEAKAGE REACTANCE IN A.C. MACHINES

The calculation of leakage reactance is rendered difficult by both theoretical complexity and manufacturing errors. The leakage is controlled by the sizes of the gaps between teeth, by the air-gap, and by the distribution of flux in these gaps. Even if the dimensions of these gaps were exactly known a precise solution would be impossible, but the practical uncertainties of a core of punched laminations make the matter doubly difficult. The end leakage, especially with machines of long coil overhang, is uncertain because of the complicated shape, and hence all leakage formulae are largely corrected by constants. It will often be found that the reactances of various members of a batch of machines, built to the same specifications by high-grade processes, differ considerably. This is particularly true of double squirrel-cage machines, on account of the depth of rotor slots.

(6) HEATING OF ELECTRICAL MACHINERY

The factor which theory is least competent to predict is heating. Any machine is an aggregation of many bodies all of differing masses, densities, specific heats, conductivities, and emissivities; some parts have heat generated in them and some are only heated by conduction; heat flow is much altered by small differences in air spacing; and most machines are artificially cooled by fans. In the face of such facts as these, any attempt at precise prediction of temperature-rise, from dimensions and physical constants alone, is obviously impracticable. Given the design data of a machine, one could estimate most of the performance data within 10 %, but an estimate of the temperature-rise obtained in the same way would probably be 50 % in error. A species of statistical calculation, based on results and rules obtained from similarly constructed machines, is all that it is profitable to attempt. Earlier treatises* usually devoted a good deal of space to predetermination of temperature-rise, but later ones† simply outline permissible temperature-rises, methods of measurement, etc., avoiding any suggestion that prediction is possible, except from experimental data. The process is almost inspired guesswork, but experience can lead to accurate results except with radically new machines.

Except descriptively, heating is an experimental subject; practically, it is of paramount importance. All machinery is sold under temperature guarantee, the limits not being in any way arbitrary but based on previous experience that if the temperatures specified are exceeded the insulation will rapidly deteriorate. In most cases the heating limit is reached before the machine is overloaded mechanically. Hence improved methods of cooling have very great economic value. Efficiency can often be better reckoned from a commercial aspect as (h.p./lb. weight) than as (power taken out/power put in), and cooling has been one of the main factors in the increase of efficiency reckoned on the first basis.*

(7) CONCLUSION

It will thus be seen that the prediction of electrical machine behaviour is both theoretically and practically complex, and that undue refinement in dealing with a particular case cannot be justified. Analytical treatment of results from a particular machine is not valuable unless it leads to a future synthesis; that is, unless it assists in the prediction of the performance of another machine. The task of the designer is to be wise before the event, and not after, and the difficulties of this have been outlined. When they are considered even such accuracy as is obtained is perhaps remarkable.

REFERENCES

(1) British Standard Specification No. 168—1936, p. 12.
(2) For example, MILES WALKER: "Specification and Design of Dynamo-Electric Machinery," 1925, pp. 218–257.
(3) For example, K. ASTON: "Design of Alternating-current Machines," 1934, pp. 338–342; also M. G. SAY and E. N. PINK: "Design of Alternating-current Machines," 1936, pp. 204–208.
(4) See, for example, D. B. HOSEASON: "Cooling of Electrical Machines," *Journal I.E.E.*, 1931, vol. 69, p. 141, especially Fig. 20.

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* See Reference (2).

† *Ibid.*, (3).

* See Reference (4).

INSTITUTION NOTES

GRADUATESHIP EXAMINATION

From November, 1939, the Graduateship Examination of The Institution will be known as the Associate Membership Examination. The change is in name only and no alteration has been made in the Examination itself.

The passing of the Examination will, as in the past, (*a*) satisfy the educational requirements for Associate Membership, and (*b*) qualify a successful candidate over 21 years of age for admission to Graduateship of The Institution.

I.E.E. REGULATIONS FOR THE ELECTRICAL EQUIPMENT OF BUILDINGS

A revised Edition (Eleventh Edition), dated June, 1939, of the above Regulations has been published. Copies can be obtained at the offices of The Institution or from the publishers, Messrs. E. and F. N. Spon, Ltd., 57 Haymarket, London, S.W.1, at the following prices:—

Bound in cloth: 1s. 6d. net (1s. 9d. post free).
Bound in paper covers: 1s. net (1s. 2d. post free).

NOMINATIONS FOR ELECTION TO THE COUNCIL

In addition to those members nominated by the Council (see vol. 84, page 769), the following have been nominated for ballot:—

As Vice-President.

C. E. FAIRBURN, M.A. (nominated by F. Bourne, J. E. Calverley, A. L. Coward, G. H. Fletcher, R. J. Harvey, Sir Arthur H. Preece, H. W. H. Richards, G. F. Sinclair, A. D. Sloan, and B. G. White, M.B.E.).

As Ordinary Member of Council (Associate Member).

F. C. ORCHARD [nominated by R. Birt, B.Sc.(Eng.), R. Illingworth, E. E. Jolly, W. E. Kidner, R. Lee, A. P. MacAlister, A. E. McKenzie, C. March, J. D. Spark, and J. Wetherell].

ROYAL NAVAL VOLUNTEER SUPPLEMENTARY RESERVE

A section of the Royal Naval Volunteer Supplementary Reserve is being formed to include men of good education and possessing engineering qualifications who are willing to perform naval service in time of war or national emergency. Those enrolled in this Reserve will not be required to undergo any naval training in time of peace but will have to undertake, if called upon, to come up for service in time of war or national emergency, when they will be given commissions as officers in the Royal Naval Volunteer Reserve and will be employed in the Navy in the capacities described below.

Candidates must have attained the age of 21 years on the 3rd June, 1939, and the normal upper age limit for retention on the List will be 30; applications to remain after that age will, however, be considered.

The capacities in which members of the R.N.V.S.R. (Engineering Section) will be employed in time of war are as follows:—

(*a*) Electrical engineers to assist Torpedo Officers in the Fleet.
(*b*) Engineers (preferably with university degrees) for duty in connection with the engines of H.M. ships.
(*c*) Engineers to assist the Technical Officers of the Fleet Air Arm.

Volunteers should apply to the Secretary of the Admiralty (C.W. Branch), Whitehall, London, S.W.1, who will forward detailed conditions of enrolment.

There are also vacancies in the Engineering Branch of the Royal Naval Reserve; but officers of the R.N.R. are required to perform training in time of peace.

OVERSEAS MEMBERS AND THE INSTITUTION

During the period 1st January to 30th June, 1939, the following members from overseas called at The Institution and signed the "Attendance Register of Overseas Members":—

Addison, J. D. (*Jaipur*).
Aitken, I. M. E., B.Sc. (*Jamshedpur*).
Bambery, C. McI. (*Palmerston, N.Z.*).
Bennett, D. P. (*Colombo*).
Beyts, Capt. W. D. H., R.E. (*Quetta*).
Brown, J. C., B.Sc. (*Lahore*).
Brown, J. F. (*Johannesburg*).
Burgess, L. F., M.C. (*Sydney, N.S.W.*).
Campbell, H. A. (*Kingston, Jamaica*).
Clark, H., B.Sc. (*Durban*).
Clarke, A. E. (*Hong Kong*).
Cook, H. F., B.Sc.(Eng.) (*Naivasha*).
Cooke, G. F. (*La Paz, Bolivia*).
Desmarais, R., B.Sc. (*Mauritius*).
Flemons, S. (*Shanghai*).
Freeman, A. C., B.E. (*Sydney, N.S.W.*).
Guilfoyle, T. J. (*Kingston, Jamaica*).
Heaume, H. Le P. (*Salisbury, Rhodesia*).
Herbert, J. F., B.E. (*Ipoh*).
Herring, E. J. C. (*Bombay*).
Homan, F. T. (*Calcutta*).
Homersham, B. R. McC. (*Christchurch, N.Z.*).
James, F. L. (*Switzerland*).
Jenkinkson, F. E. (*Port Elizabeth*).
Kirk, G. L. (*Colombo*).
MacMuldrow, W. G. P. (*Umvuna*).
Malegamvala, D. K. (*Bombay*).
Martin, G. E., M.A. (*Bombay*).
Millman, C. H. (*Delhi*).
Myers, D. M., B.Sc., B.E. (*Sydney, N.S.W.*).
Parkinson, J. D. (*Hong Kong*).
Payne, D. H. (*Lagos*).
Peterson, I. E. K. (*Khewra*).
Pomroy, R. O. (*Sydney, N.S.W.*).
Preston, C. E., M.Eng. (*Hyderabad*).
Randall, W., M.C. (*Asansol*).
Ridley-Martin, R. B. (*Khartoum*).
Sale, H. G. (*Bombay*).
Silverman, D. (*Cairo*).
Steel, C. S. (*Calcutta*).
Stevenson, I. D. (*Wellington, N.Z.*).
Stubbs, W. (*Kuala Lumpur*).
Targett, E. H. (*Colombo*).

Taylor, L. F., B.Sc.(Eng.) (*Oshogbo*).
Turrell, F. H., B.Sc.(Eng.) (*Johore*).
Tyacke, J. A., B.Sc. (*Ipoh*).
Webb, C. R. (*Shanghai*).
Williams, J. W. M. (*Nairobi*).
Wright, R. (*Buenos Aires*).

INFORMAL MEETINGS

223rd Informal Meeting (6th February, 1939)

(Joint meeting with The Institution of Civil Engineers and The Institution of Mechanical Engineers.)

Chairman: Mr. P. P. Wheelwright.

Subject of Discussion: " The Preparation and Giving of Expert Evidence " (introduced by Mr. J. H. Rider).

Speakers: Messrs. J. D. C. Couper, W. A. Tookey, F. C. Raphael, D. Winton Thorpe, A. Morgan, A. F. W. Richards, S. C. Bartholomew, M.B.E., H. Nimmo, B. Irvine, J. Scott-Taggart, G. O. McLean, M.Eng., J. E. Kingsbury, F. L. Veale, and C. W. G. Roberts.

224th Informal Meeting (20th February, 1939)

Chairman: Mr. J. R. Jones.

Subject of Discussion: " The Steam Cycle " (introduced by Mr. E. L. Luly).

Speakers: Messrs. R. A. W. Connor, W. S. Burge, J. F. Field, B.Sc., B. Wood, M.A., G. O. McLean, M.Eng., S. D. Whetman, B.Sc., G. E. Richardson, and J. R. Jones.

225th Informal Meeting (13th March, 1939)

Chairman: Mr. M. Whitgift.

Subject of Discussion: " The Automatic Voltage Control of Low-Tension Networks " (introduced by Mr. R. H. Upton, M.Eng.)

Speakers: Messrs. H. S. Petch, B.Sc.(Eng.), F. Jervis Smith, G. O. McLean, M.Eng., W. F. Sands, J. R. Haslam, B.Sc.(Eng.), G. H. Fowler, E. T. Norris, R. Grierson, A. G. Kemsley, P. P. Wheelwright, W. A. Ritchie, W. Hill, W. A. Wood, A. E. Morgan, S. A. Stevens, and G. B. Proctor, B.Sc.Tech.

226th Informal Meeting (27th March, 1939)

Chairman: Mr. P. H. Pettifor, B.Sc.(Eng.).

Subject of Discussion: " Electric Battery Vehicles and Future Possibilities " (introduced by Mr. G. O. McLean, M.Eng.).

Speakers: Messrs. C. W. Marshall, W. E. Warrilow, C. G. F. Pritchett, L. Murphy, E. S. New, A. G. Kemsley, Major T. Rich, Major A. L. Trundle, Messrs. W. T. Gemmell, H. G. Wilson, P. P. Wheelwright, I. O. Hockmeyer, B.Sc.(Tech.), J. M. Kennedy, and F. Jervis Smith.

227th Informal Meeting (3rd April, 1939)

Chairman: Mr. W. A. Ritchie.

Subject of Discussion: " Electric Signs " (introduced by Mr. A. H. Brackensey).

Speakers: Messrs. P. H. Pettifor, B.Sc.(Eng.), I. O. Hockmeyer, B.Sc.Tech., S. C. Bartholomew, M.B.E., F. Jervis Smith, R. W. Presswell, W. Bamford, P. P. Wheelwright, G. H. Fowler, G. Davidson, E. Brown, and F. Peake Sexton.

PROCEEDINGS OF THE METER AND INSTRUMENT SECTION

80th Meeting of the Meter and Instrument Section, 4th November, 1938

Mr. H. Cobden Turner, the retiring Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 20th May, 1938, were taken as read and were confirmed and signed.

Mr. Cobden Turner announced the Council's award of Premiums (see vol. 82, page 699), for papers read before the Section during the session 1937–38. He then vacated the chair, which was taken by the new Chairman, Captain B. S. Cohen, O.B.E.

A vote of thanks to Mr. Cobden Turner for his services as Chairman during the session 1937–38, proposed by Mr. F. E. J. Ockenden and seconded by Dr. H. M. Barlow, was carried with acclamation.

Captain Cohen then delivered his Inaugural Address (see vol. 84, page 237).

A vote of thanks to the Chairman for his Address, proposed by Mr. F. C. Knowles and seconded by Mr. G. A. Whipple, was carried with acclamation.

81st Meeting of the Meter and Instrument Section, 9th December, 1938

(Joint Meeting with the Physical Society.)

Captain B. S. Cohen, O.B.E., Chairman of the Section, took the chair at 7 p.m., supported by Prof. A. Ferguson, M.A., President of the Physical Society.

The minutes of the meeting held on the 4th November, 1938, were taken as read and were confirmed and signed.

An informal discussion, opened by Dr. C. V. Drysdale, C.B., O.B.E., took place on " Electro-Acoustics."

At the conclusion of the discussion a vote of thanks was accorded to Dr. Drysdale for his introductory remarks, and was carried with acclamation.

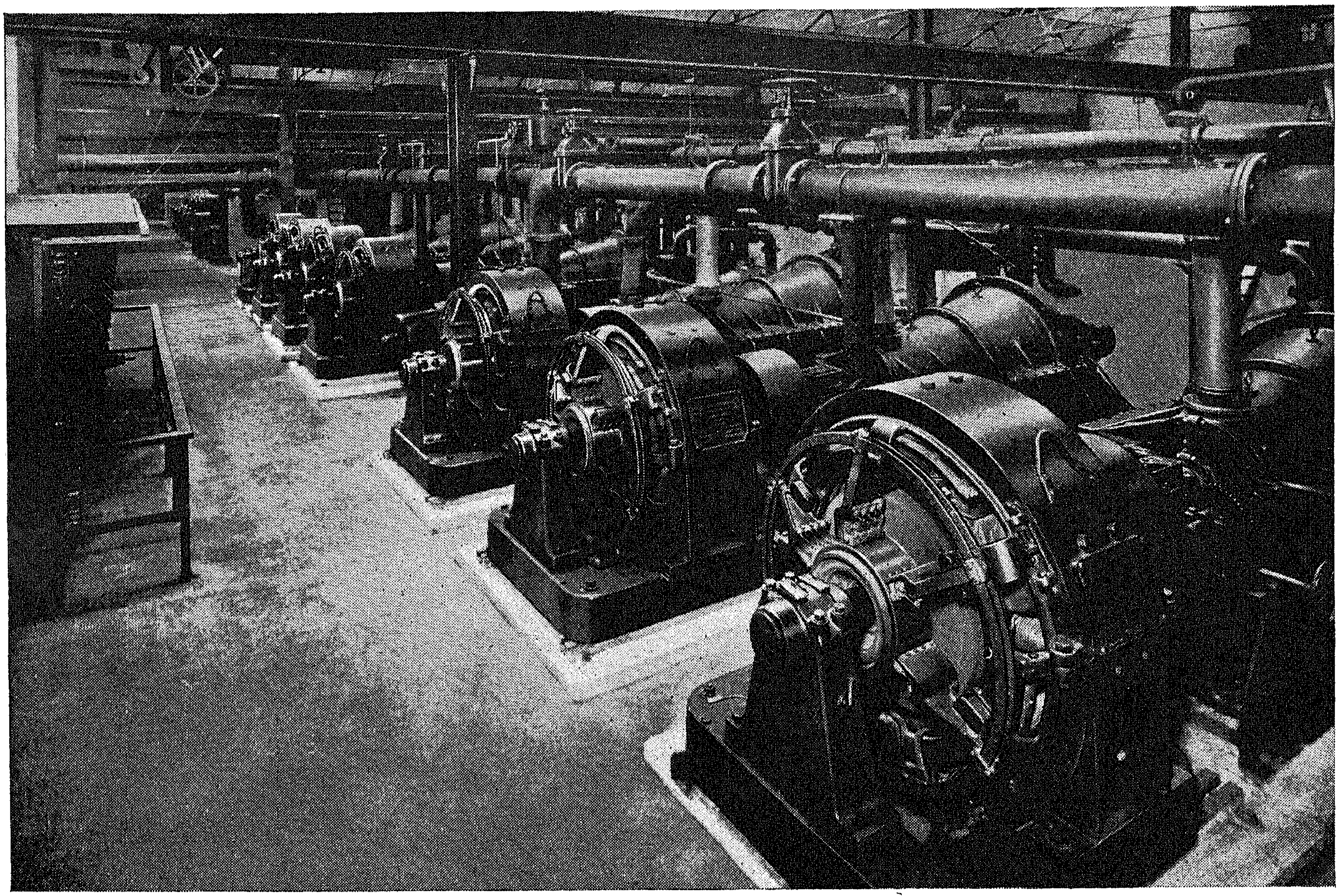
82nd Meeting of the Meter and Instrument Section, 6th January, 1939

Captain B. S. Cohen, O.B.E., Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 9th December, 1938, were taken as read and were confirmed and signed.

A paper by Messrs. E. G. James, B.Sc., Ph.D., G. R. Polgreen, B.Sc., Member, and G. W. Warren, B.Sc., entitled " Instruments Incorporating Thermionic Valves, and their Characteristics," was read and discussed. The paper was accompanied by a demonstration of apparatus.

A vote of thanks to the authors, moved by the Chairman, was carried with acclamation.



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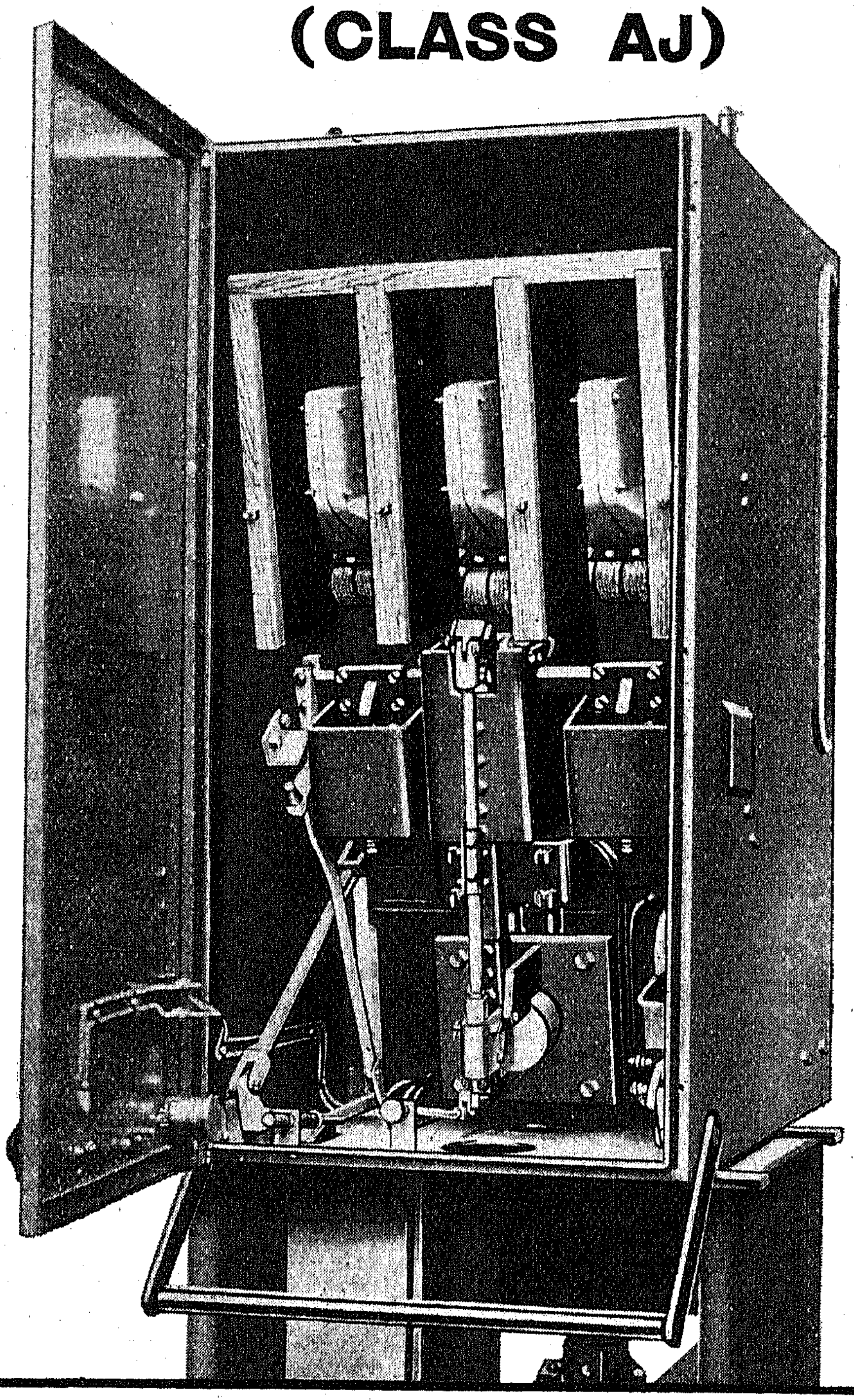

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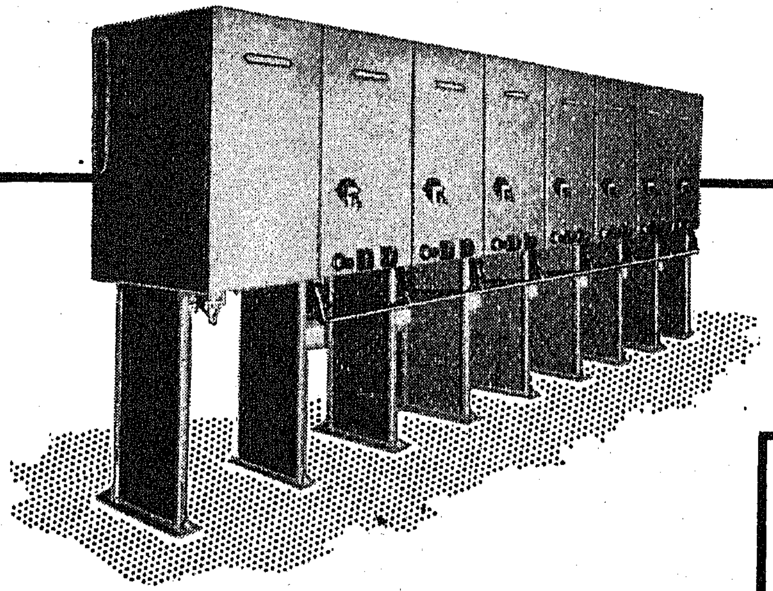

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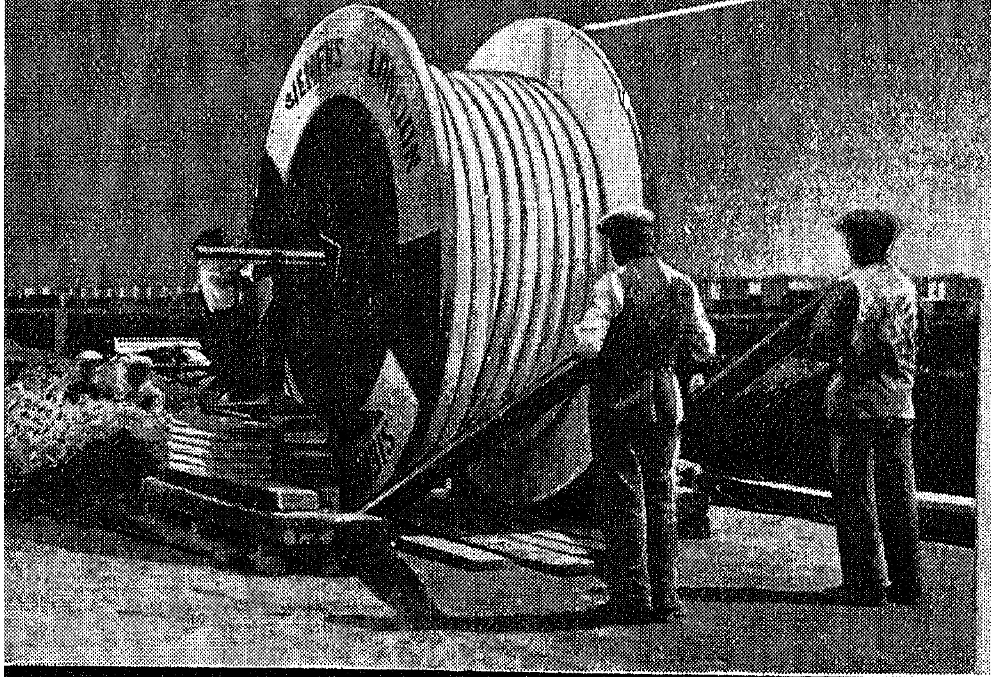

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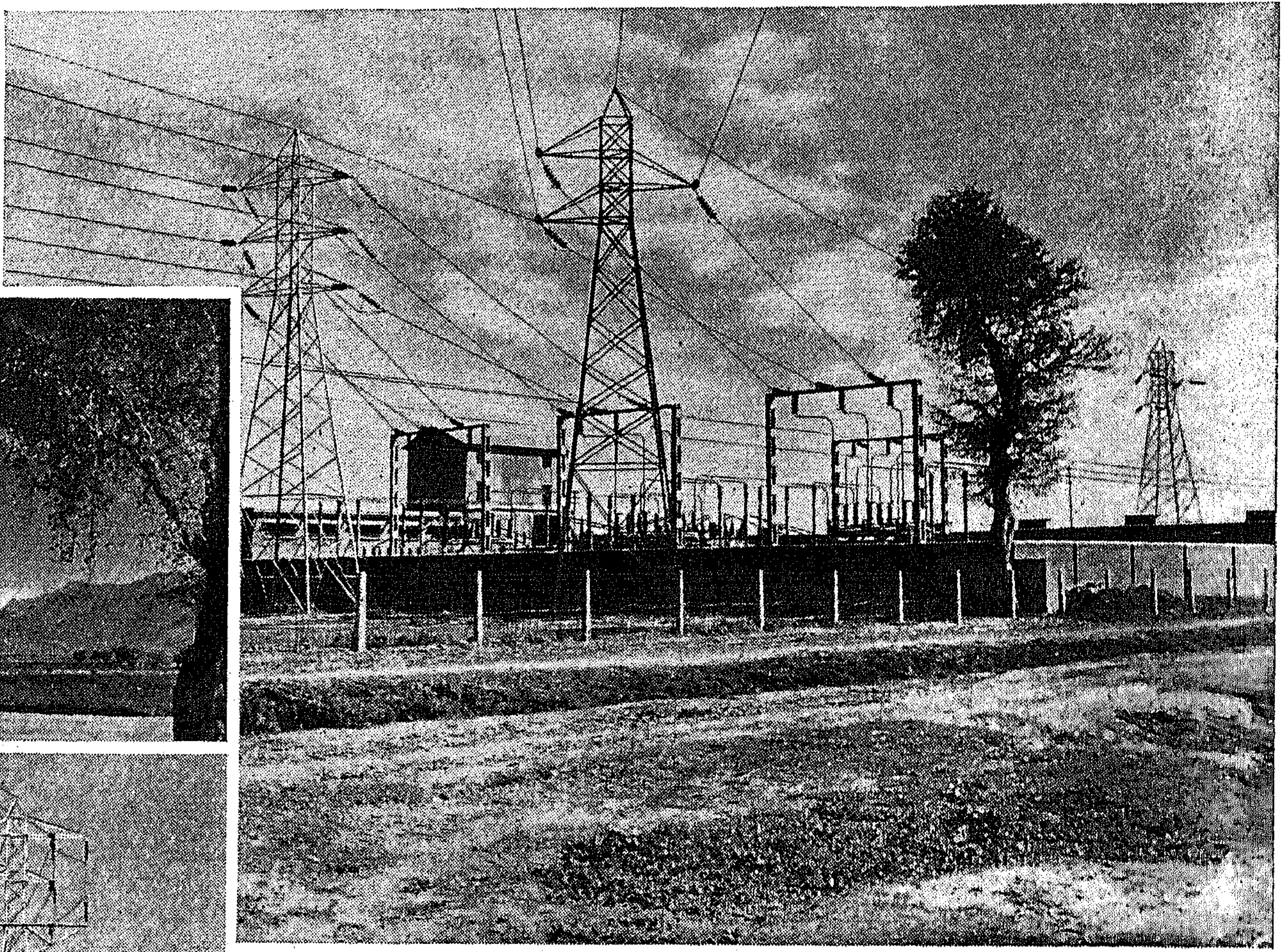

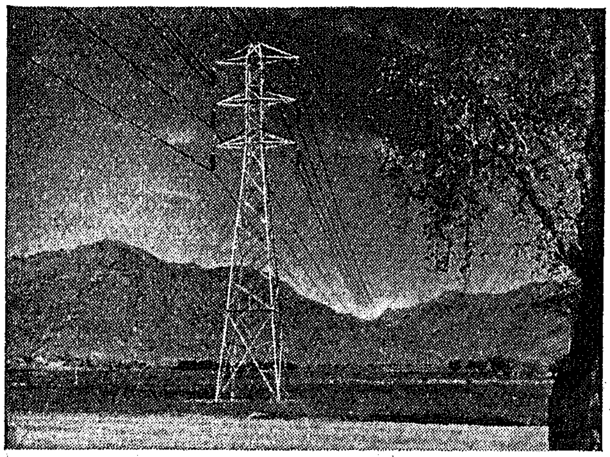

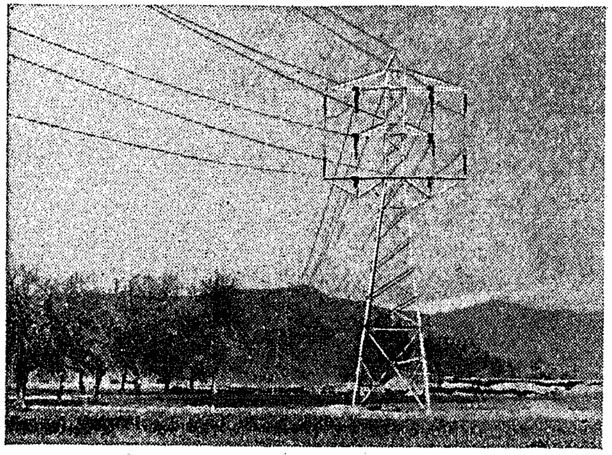

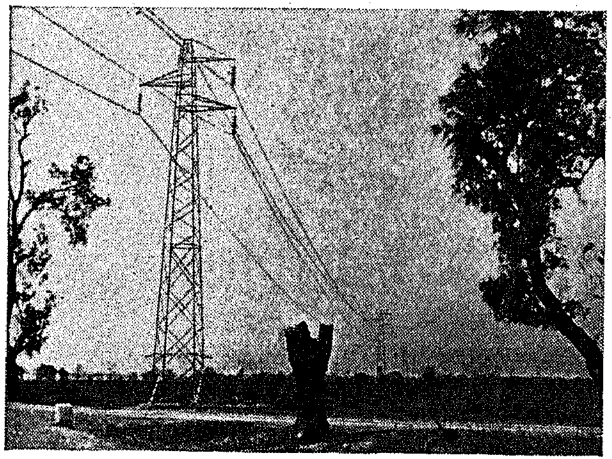

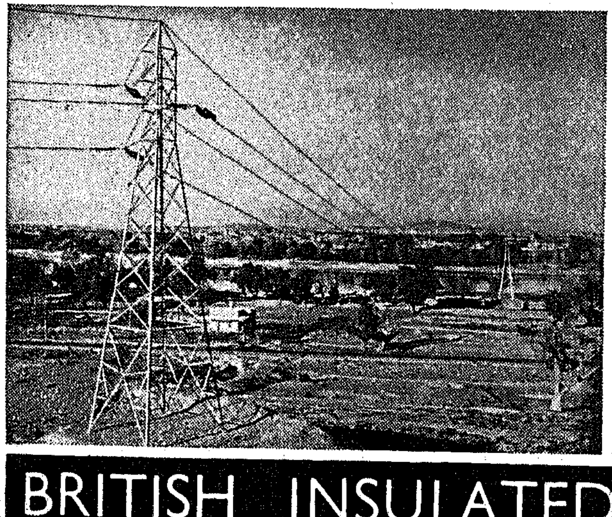

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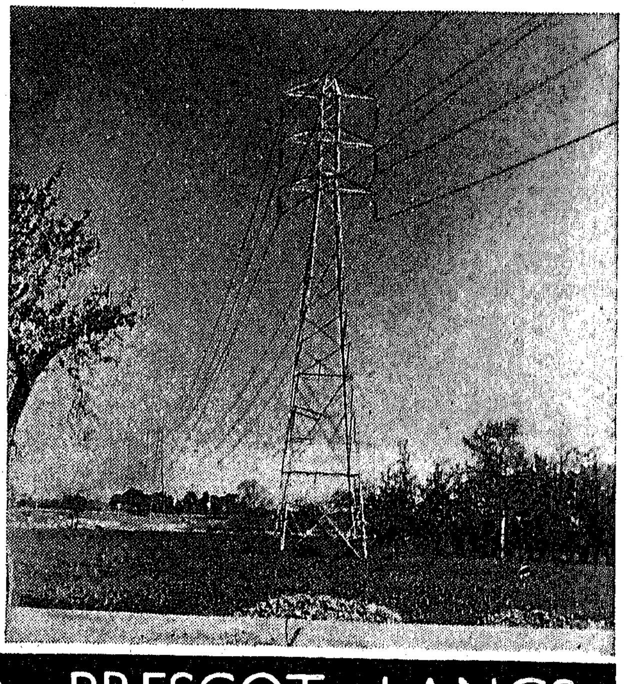

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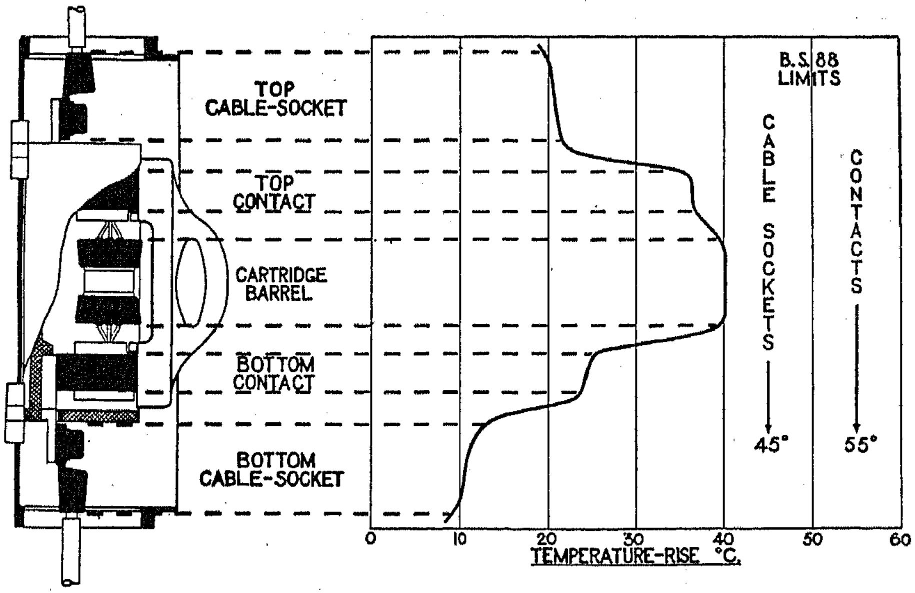

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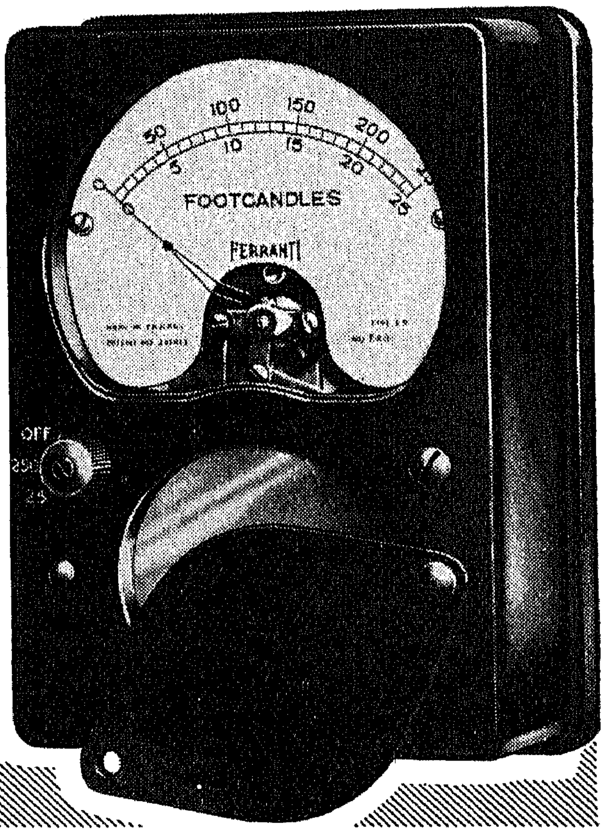

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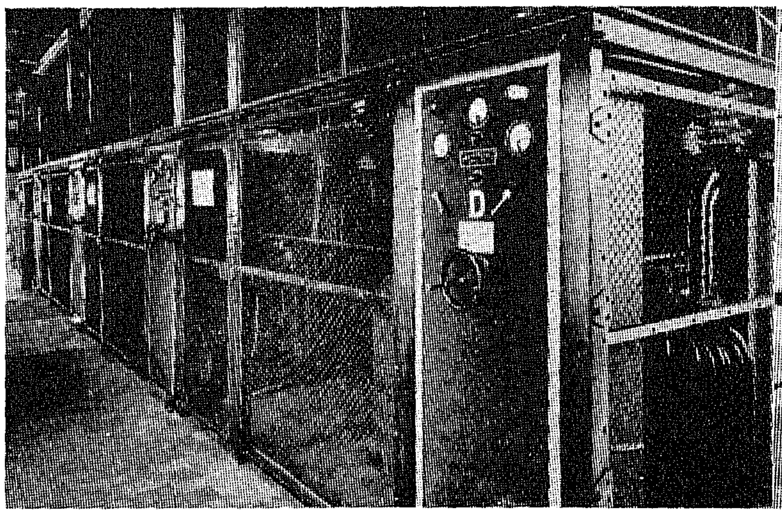

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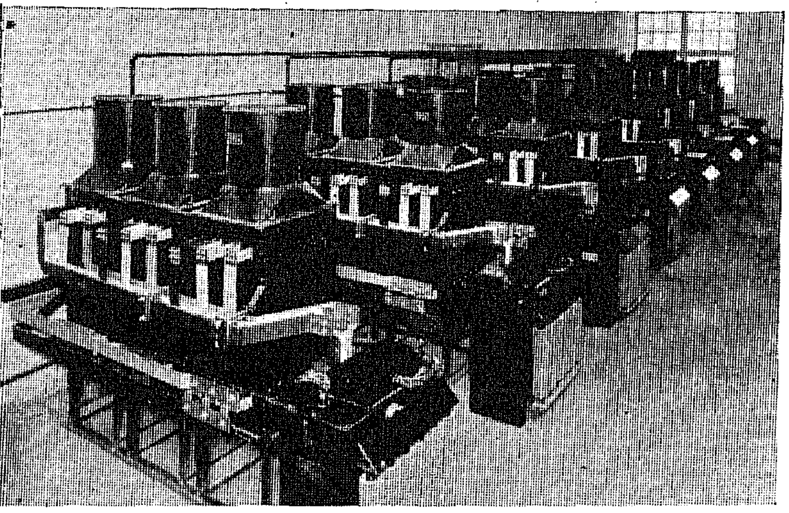

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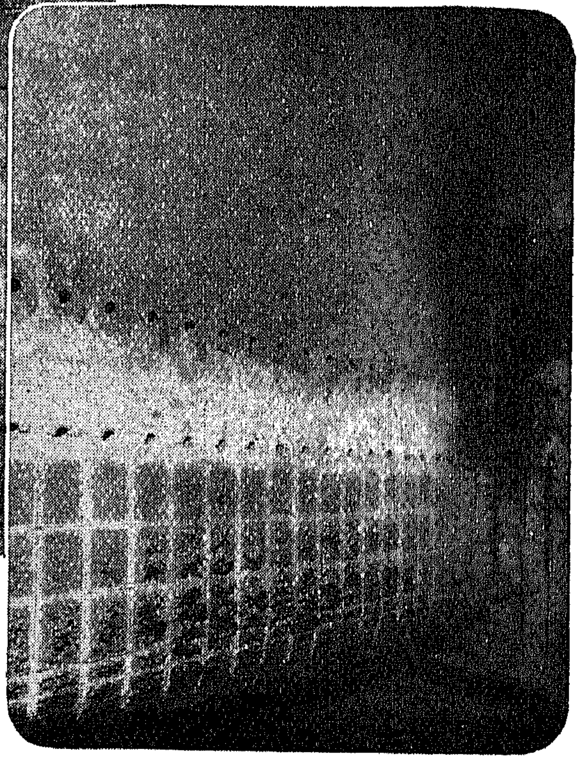

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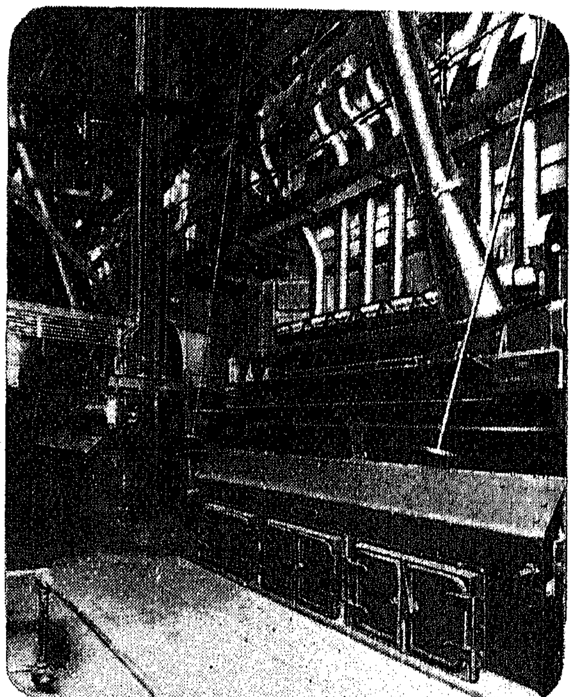

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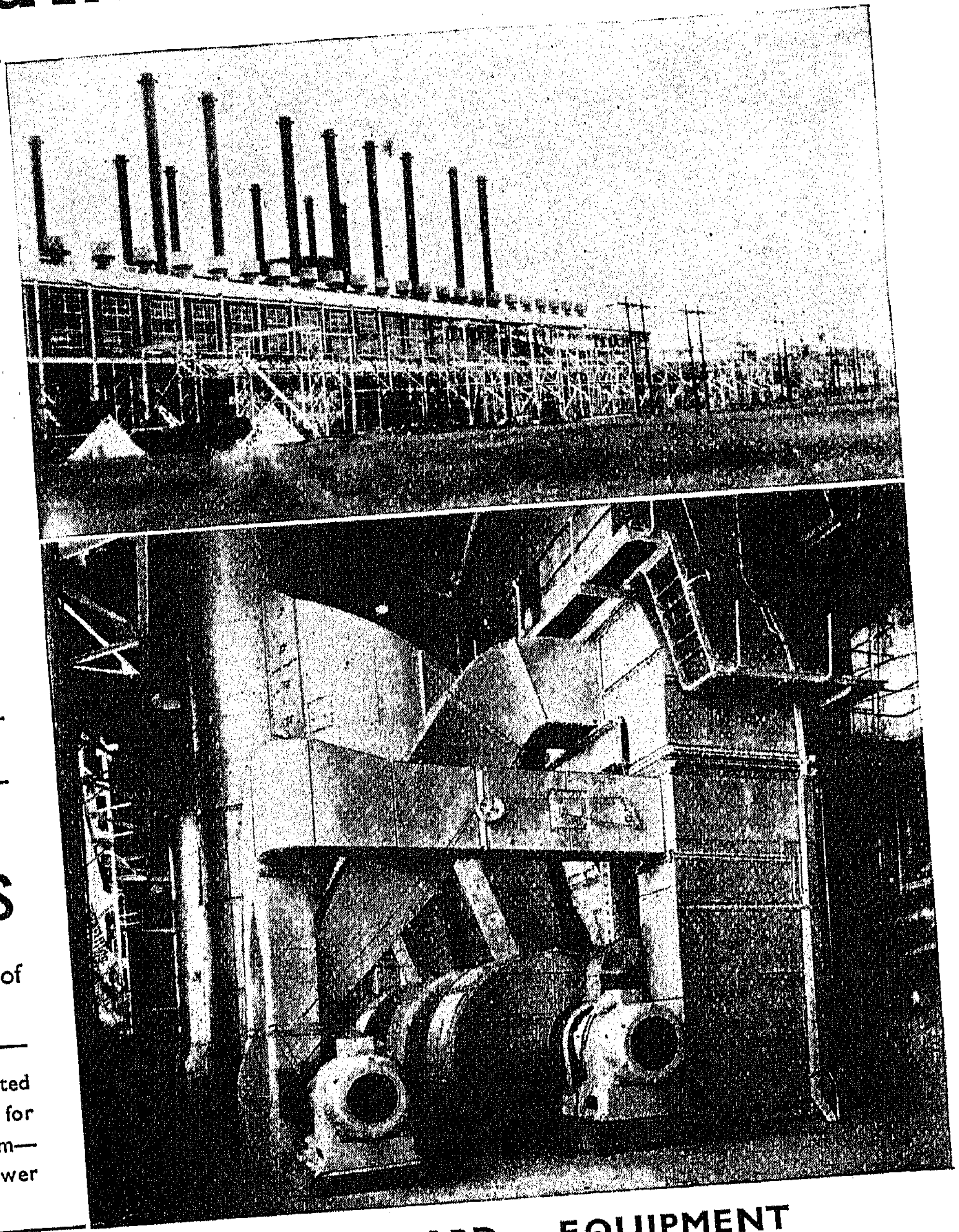

ILLUSTRATIONS: Top—Klip Power Station constructed by Victoria Falls and Transvaal Power Co. Ltd., for Electricity Supply Commission, S. Africa. Bottom—"Sirocco" Mechanical Draft Installation at Klip Power Station.

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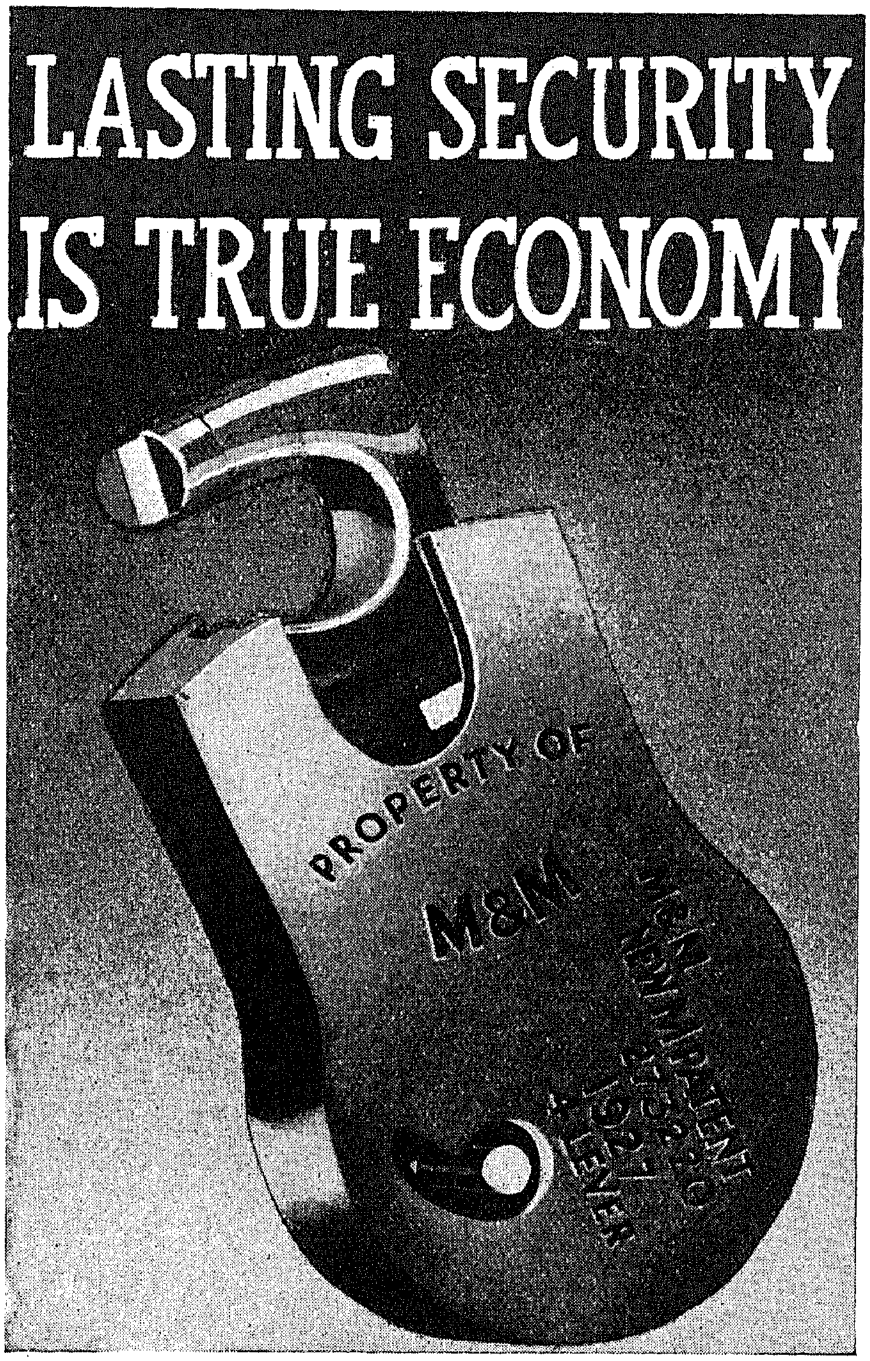

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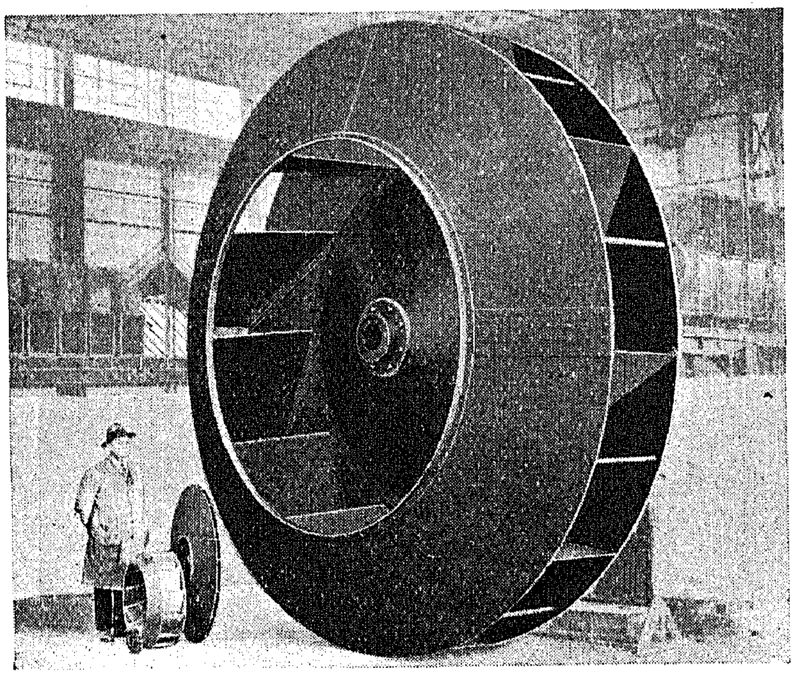

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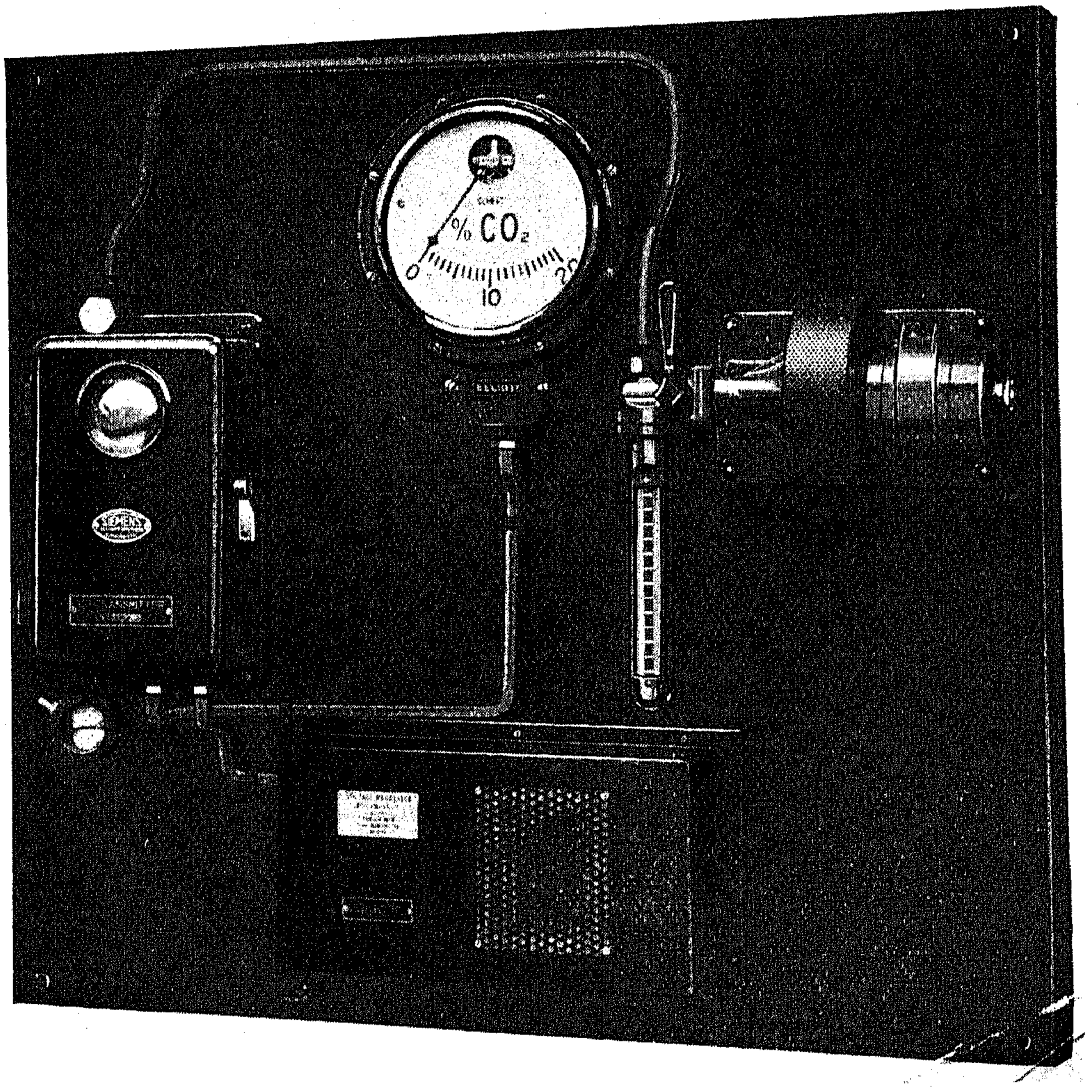

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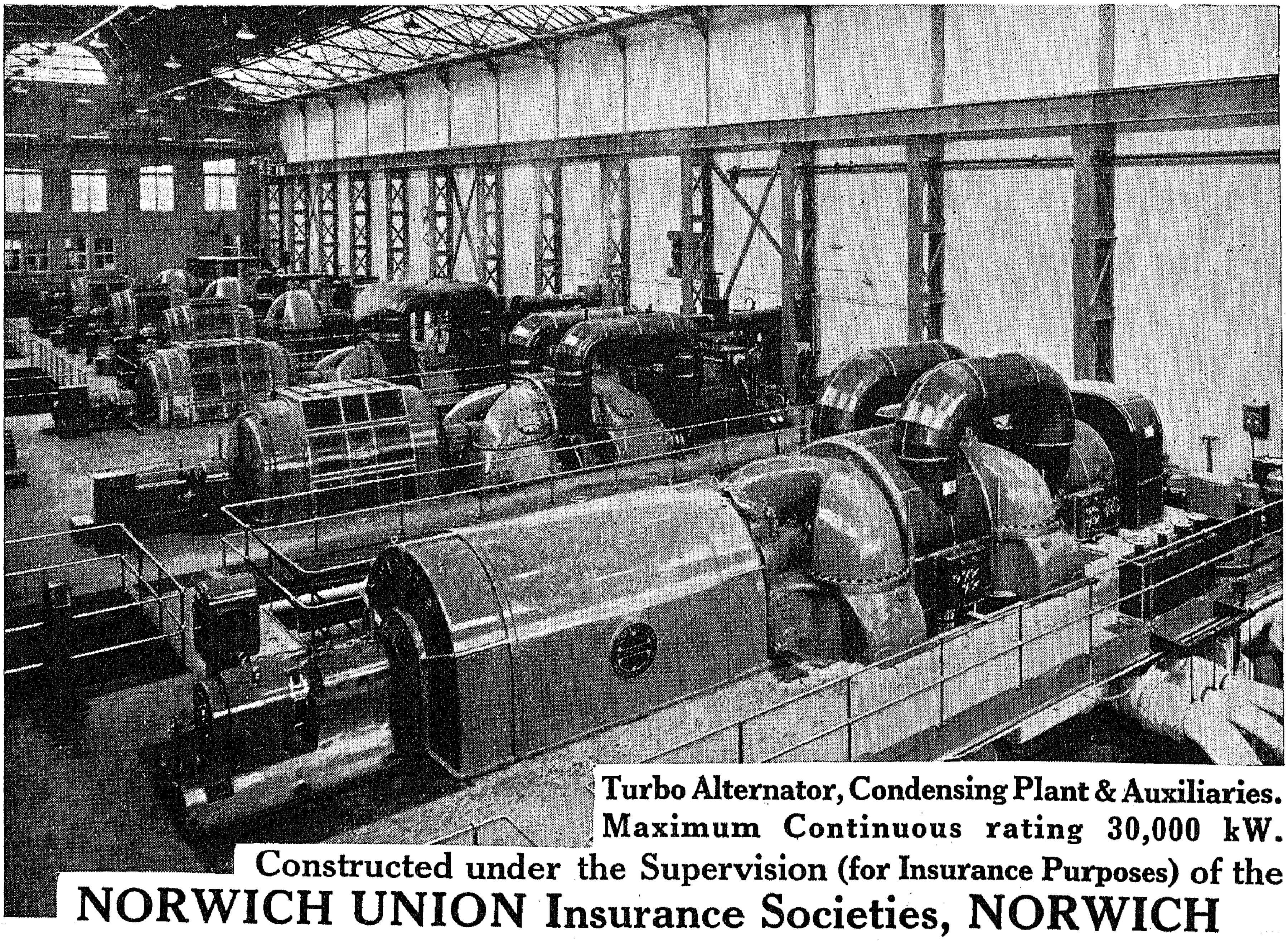

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LIST OF ADVERTISERS IN THIS ISSUE

	PAGE
Automatic Coil Winder & Electrical Equipment Co., Ltd.	xv
Babcock & Wilcox, Ltd.	x
British Insulated Cables, Ltd.	iv
British Thomson-Houston Co., Ltd.	ii
Cable Makers' Association	vi
Davidson & Co., Ltd.	xi
Ebonestos Industries, Ltd.	xii
Elliott Brothers (London), Ltd.	xiii
Ferranti, Ltd.	vii
General Electric Co., Ltd.	i
Keith Blackman, Ltd.	xiii
Mitchell (H.) & Co.	xii
Muirhead & Co., Ltd.	viii
Nalder Brothers & Thompson, Ltd.	xv
Norwich Union Insurance Societies	xiv
Reyrolle (A.) & Co., Ltd.	v
Siemens Brothers & Co., Ltd.	iii
Standard Telephones & Cables, Ltd.	xvi
Westinghouse Brake & Signal Co., Ltd.	ix
Zenith Electric Co., Ltd.	xv